SUBMARINE DETECTION

IN AN

ALTERNATING MAGNETIC FIELD

BY

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AND

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March 1919.

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SUBMARINE DETECTION
IN AN
ALTERNATING MAGNETIC FIELD.

An experimental investigation conducted
under the direction of the Special Problems Committee
of the Naval Consulting Board of the United States.

By

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Official Report:

J. B. Whitehead
Major, Engineers, U. S. A.,
In charge of the experiments.

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March 1919

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J. B. WHITEHEAD AND L. O. GRONDAHL.

INTRODUCTION.

Shortly after the entrance of the United States into the war, these experiments were begun by Professor Whitehead, at the request of Major Ralph D. Mershon, Engineers, U. S. R., assigned to duty with the Naval Consulting Board, and in general charge of work conducted by the Special Problems Committee, B. G. Lamme, Chairman. The fundamental idea on which the experiments are based was first suggested by Major (now Lieutenant Colonel) Mershon.

In June, 1917, Professor Whitehead was commissioned Major, Engineers, U. S. R., and later assigned to duty with the Naval Consulting Board, for the continuation of this work.

The first experiments were conducted in the Laboratory of Electrical Engineering of The Johns Hopkins University, Baltimore, Md., with the consent and active cooperation of the University authorities. By far the larger part of the experimental equipment for the Baltimore tests, as well as that for the tests at Annapolis and on shipboard, was loaned by the University. In addition, its power plant and the services of its shop and office forces were freely drawn upon.

The Annapolis tests were conducted at the Engineering Experiment Station, U. S. Naval Academy, where active and invaluable assistance was given by Rear Admiral T. W. Kinkaid, Head of Station, and his staff.

Through the Special Board of the Navy Department at New London, Submarine Chaser No. 326, stationed at Annapolis, was put at the disposal of the Naval Consulting Board for the tests afloat. Every courtesy and facility was offered by Rear Admiral Edward Lloyd, and by Chief Boatswain A. R. Mulkins, commanding "S. C. #326", and his crew.

Important assistance was also rendered by the engineering staffs of several manufacturing companies, particularly those of the Westinghouse Electric & Manufacturing Co., the Western Electric Co., and the Weston Electrical Instrument Co.

Especial thanks are due Dr. W. B. Kouwenhoven, Associate Professor of Electrical Engimeering, Johns Hopkins University, during the early stages of the work, and throughout to Mr. Joseph Weil, assistant, Frank Skrivan, electrician, and Sam Styers, mechanician, for enthusiastic and expert services.

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SUMMARY OF RESULTS.

If a submarine approaches a vessel carrying a magnet excited by alternating current, the submarine will be magnetised or will have electric currents set up in its hull. Either phenomenon will distort the original field of the magnet.

If a detecting coil be placed in the undistorted field and the electromotive force in it be completely neutralized, when the submarine approaches an alternating current will be set up in the detecting coil.

Laboratory tests of the above plan were conducted with submarine models 10 ft. long. The results are shown to agree with underlying theory, and served for the design of larger equipment.

Detection tests, using steel surface vessels, were conducted at Annapolis with magnet and coils on shore. The results corroborated the predictions from the earlier laboratory tests.

Detection tests were conducted afloat with equipment especially constructed for assembly on Submarine Chaser #326, a wooden vessel 110 ft. long. Surface vessels were used in these tests.

All of the results agree approximately with formulae developed for the design of the equipment, and indicate that by a sufficient increase in the size of the equipment it should be possible, in quiet water, to reach distances of detection up to 500 ft. The weight of the equipment necessary for this purpose would be in the neighborhood of 8000 pounds.

Distances of detection in the neighborhood of 200 ft. were obtained with the equipment on Submarine Chaser #326. The weight of this equipment was about 4500 pounds.

The extreme accuracy necessary in the electric adjustments impose a serious, if not prohibitive, limitation on the use of the device in rough water, or under sudden changes of the speed or the course of the ship.

Conclusions are drawn as to the directions in which improvement may be looked for, as regards both distance of detection and stability in rough water.

A number of interesting auxiliary experiments on the limits of sensitivity, elimination of disturbances, accurate speed control, etc., are described in a series of appendices.

An investigation, of the possibility of using the steel hull of a vessel as a magnet, extended through a series of laboratory tests, but could not be carried further. (See Appendix H).

SUBMARINE DETECTION IN AN ALTERNATING MAGNETIC FIELD.

GENERAL DESCRIPTION.

Of the various devices suggested for the detection of a submerged submarine, probably the simplest and most obvious are those making use of the magnetic and electrical properties of the hull. If the submarine comes into a magnetic field it becomes magnetised and consequently its presence may be detected by suitable measuring instruments. For example, if a detecting vessel carries a magnet or is itself magnetised, a submarine in its neighborhood will become magnetised. A suitable detecting instrument on the detecting or searching vessel will then indicate the presence of the submarine, particularly if the instrument is compensated against the influence of the field of the magnet itself.

If the magnet be excited by alternating current, the magnetic field will be alternating. The principle of the device tested in the experiments described in this paper will be best understood from the following description by Lieutenant Colonel Ralph D. Mershon, Corps of Engineers, U. S. A., to whom the suggestion is originally due, and whose constant interest and cooperation have contributed largely to whatever success has attended the progress and results of the work:

"An alternating magnetic field may be made use of to detect and to locate invisible objects, provided the object to be so detected and located has certain characteristics."

"(a) If the object has magnetic properties and is not capable of having currents induced in it, then it must be either more

magnetic (more permeable), or less magnetic than is the volume of the surrounding medium which it displaces."

"(b) If the object has not magnetic properties it must be capable of having currents induced in it either more readily or less readily, (i. e., it must be either more conducting or less conducting to induced currents) than the volume of the surrounding medium which the object displaces."

"(c) If the object falls in both of the classes (a) and (b), that is, if it is either more magnetic or less magnetic, and at the same time is either more conducting or less conducting than immersing medium, then, in general, it may be detectable or not detectable, depending upon the particular combination of the two qualities it has, and the frequency employed."

"If this method of detection and location be applied to the submarine problem the conditions we shall expect to meet are these: Either the object, the submarine, will be non-magnetic and more conducting than the volume of the immersing medium which it displaces; as, for instance, if it were made of bronze or of non-magnetic steel. Or it will be more magnetic (more permeable) than the immersing medium and more conducting than the immersing medium; as, for instance, if it is made of magnetic steel."

"In the former case it must be detected by means of currents induced in it. In the latter case it may be detected either by currents induced in it, or by its magnetic properties. But, in general, it cannot be detected by both, since they tend to act oppositely. And there will be some frequency at which the induced current effects and the magnetic effects will practically neutralize each other, so that at this particular frequency the submarine cannot be detected."

"Detection by means of induced currents is better carried out by an alternating field of relatively high frequency; while detection through magnetic properties is better accomplished by an alternating field of low frequency."

"The most promising method so far proposed for the detection of submarines by an alternating magnetic field is this: An alternating magnetic field is set up by an alternating current magnet having an open magnetic circuit; - a straight bar magnet so designed as to give as far reaching and as strong a field as is practicable. In the field of this magnet, and as far away from it as is practicable, is located a detecting coil. This coil may be located with its plane parallel to the lines of force set up by the magnet, in which case it will theoretically have no voltage induced in it by the magnet itself; or, it may be located with its plane not parallel to the lines of force, in which case the voltage induced in it by the alternating field set up by the magnet must be balanced out by another electromotive force exactly opposed in phase and magnitude to the voltage induced in the detecting coil. If the conditions aimed at are realized, there will, in either of these cases, be no resultant electromotive force in the circuit including the detecting coil, and no indication thereof in such means as may be employed for detecting an alternating e.m.f. in this circuit. If, now, a submarine comes into the field set up by the magnet, the submarine will disturb the field existing around the detecting coil, with the result that there will be an alternating voltage produced in the detecting coil circuit which will indicate the presence of the submarine, and may also indicate its location."

The current due to the electromotive force induced by the submarine in the detecting coil may be measured in a number of ways

and in particular it may be rectified by a commutator mounted on the shaft of the generator supplying the magnet, and the signal read on a D. C. measuring instrument. The use of an alternating magnetic field and a commutator has a number of advantages. The system is independent of motion in the earth's magnetic field. It has a selective property, since the commutator will chop up disturbances of lower frequency. Under certain circumstances disturbances of higher frequency may be filtered out by suitable combinations of inductance and capacity. The signal e.m.f. is received in a detecting coil and an increase in the size of this coil affords one way of increasing the magnitude of the signal received from the submarine and therefore increasing the distance of detection. The e.m.f. in the detecting coil due to the magnet itself may be balanced out in a number of simple ways. Finally by means of the commutator a continuous current detecting instrument may be used.

As is well understood, the strength of the magnetic field due to a magnet falls off very rapidly with increasing distance from the magnet. For distances large in comparison with the magnet, the strength of field is inversely as the cube of the distance from the magnet; that is to say, the strength of magnetic field at the submarine will be inversely as the cube of its distance from the magnet. This is a serious enough limitation, but is nevertheless only half the story in submarine detection. For detection of the presence of the submarine it is necessary that the magnetised submarine itself set up a field at the detecting coil sufficient to generate in that coil an electromotive force which may be detected by the usual available types of detecting instrument. This return signal from the submarine varies also inversely as the cube of the distance. Consequently, the signal in our detecting coil will vary roughly

inversely as the sixth power of the distance to the submarine.

The relations outlined in the foregoing paragraph are at first sight most discouraging and indeed apparently insuperable. There are, however, several ways in which much of the handicap of the inverse sixth power may be wiped out. In the first place, the dimensions of the modern submarine are so great that its magnetic moment, even in a field of low intensity, may still be of appreciable magnitude. The signal received in the detecting coil may be increased by increasing the volume of the coil. The strength of the magnetic field at the submarine may obviously be increased by increasing the size of the magnet. And finally, we have now available in the three-electrode aplifier or pliotron tubes a means for stepping up a minute electric signal several hundreds of thousands of times. With the use of such tubes, it is theoretically possible to offset in large measure the limitation imposed by the inverse sixth power of the distance and to reach distances of detection which would be extremely important in submarine warfare, if realized.

It is obviously possible to compute approximately the moment of a magnet necessary for setting up a given field strength at a given distance. But it is not possible to predict the magnetic moment of a submarine when in this field. It is also known how much the e.m.f. induced in a detecting coil will be multiplied by the use of amplifier tubes. The fundamental laws being known, it would appear therefore that experimental determinations of the magnetic properties of the hull of a submarine, and of the limits of sensitivity available with amplifier tubes, should offer a reliable basis for the design for a large equipment.

As regards the magnetisation of a submarine, if it were placed in a uniform magnetic field in the direction of its axis, it

would still be impossible, owing to its unsymmetrical shape, the riveting of its plates and the uncertainty as to its interior structure, to make even an approximate estimate of its magnetic moment. Aside from this, the shell of the submarine when placed in an alternating magnetic field will have set up in it circulating or secondary currents. The magnetic field due to these secondary circuits will, in general, differ both in magnitude and in phase from that due to the magnetisation of the hull. The relative importance and net magnetic moment due to these influences are obviously matters for experimental determination.

There is, however, one further important and indeterminate factor. The detecting coil, in view of its position on the detecting vessel, will be relatively close to the magnet, consequently it will have induced in it a large electromotive force due to the magnet. This electromotive force must be balanced out and the coil be retained, as far as possible, in a neutral electric condition, for this is the condition of maximum sensitivity toward the signal from the submarine. This consideration demands as nearly as possible a rigid relation in space between the magnet and coil. On shipboard it is a question as to just how definitely it is possible to retain such a fixed relation. In considering this question it appeared certain that vibration and motion of a boat, due to its driving machinery and to its rolling in a heavy sea, would, to a greater or less extent, upset this desirable rigid relation between magnet and coil. The exact amount of this upset and whether it would be great enough to seriously impair the method are also questions to be answered only by actual tests.

OUTLINE OF EXPERIMENTS.

Since the underlying relations of the method are reasonably clear, the uncertain factors being the values of the constants involved, the problem was first attacked by laboratory tests aimed to determine whether distances of detection which would be actually useful could be reached. Using the constants obtained in these laboratory tests, it should be possible to compute distances of detection when larger equipment is used.

Tests of this character were carried out in the Laboratory of Electrical Engineering of The Johns Hopkins University. In the following pages these tests will be described first and the computations upon which the design of the larger equipment was based will be given.

Next there will be described a series of experiments conducted at the Engineering Experiment Station at the United States Naval Academy, at Annapolis, Md. In these experiments magnet and coils of quite large size were used, the magnet and coils being placed on the end of a pier and detection tests conducted with the use of steel vessels. These tests were undertaken particularly to check the accuracy of the conclusions of the work at Johns Hopkins University. At a time when all types of naval vessel were in great demand, it was thought advisable not to divert from other uses a boat for these detection tests unless it were reasonably certain that useful distances of detection could be obtained. The conditions at the Engineering Experiment Station were such as to make it a fairly simple matter to conduct these tests. The magnet and coils were made quite large so as to test their values for increasing the distance of detection.

The tests at the Engineering Experiment Station show a very good agreement with the distances computed from the Baltimore tests. It was therefore determined to put the equipment on shipboard and for this purpose a 110 ft. submarine chaser (S. C. #326) was used. Since the large magnet, coils and motor generator used at the Experiment Station were too heavy for the chaser, an intermediate equipment was constructed suited to the space available.

The description of all the experiments will be given as concisely and directly as possible in terms of the final results of each set of experiments. Throughout the work there have arisen numerous difficulties and necessity for many auxiliary tests. Some of these tests are of considerable interest. In order that they may not obscure the principal thread of the report, these auxiliary tests, as well as all descriptions of technique, have been included in the form of appendices following the principal part of the report.

TESTS AT JOHNS HOPKINS UNIVERSITY.

The tests at Johns Hopkins University comprised studies of the types of magnet and detecting coils, of the method of balancing the electromotive force in the detecting coil due to the magnet, various types of commutator and detecting instrument, the use of amplifying tubes, the choice of alternating frequency, types of speed control and tests of the formulae by which the results to be expected in actual service are computed. Each of these investigations has contributed to the design of the final equipment. The successive steps in each of these studies appear to be of interest and value but have no necessary place in a direct statement of the experiments and conclusions of this investigation. Therefore each of these separate studies will be described in an appendix.

The following description covers the final detection tests made in the laboratory, the apparatus and plan being based on the conclusions from the preliminary studies mentioned. It will be understood that the initial experiments involved the simplest elements of the method and that successive improvements and additions to these elements have resulted in better conditions of observation and greater distances of detection leading up to the final laboratory tests described below.

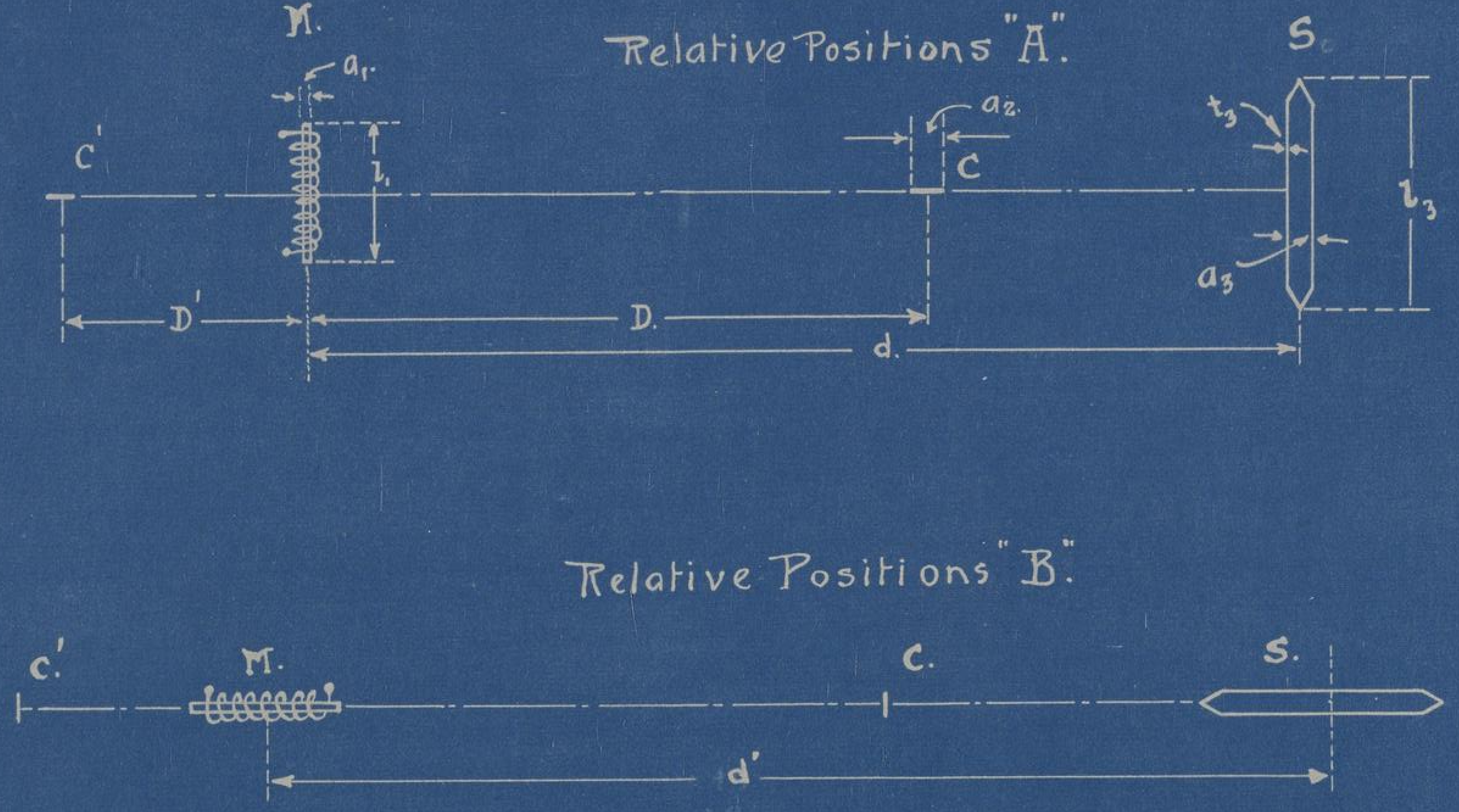
The general arrangement of the essential elements is shown in Fig. 1 and the electric connections in Fig. 2. Referring to Fig. 1, S is a model submarine, M is the magnet excited by alternating current, C is a detecting coil and C' a balancing coil. Two arrangements of the relative positions of S, C and M are shown, these being the two most important from the standpoint of detection at a distance.

SUBMARINE MODEL S_0.

The model was made of galvanized iron .025 in. thick. It was cylindrical in shape with conical ends, the altitude of these ends being one foot. The length over all was 10 ft. and the diameter 1 ft. The length, diameter and thickness of wall are in approximately the same ratios as those pertaining to a late type of submarine of length 200 ft. There were five sections in the model, including the ends, the joints being telescoped without soldering.

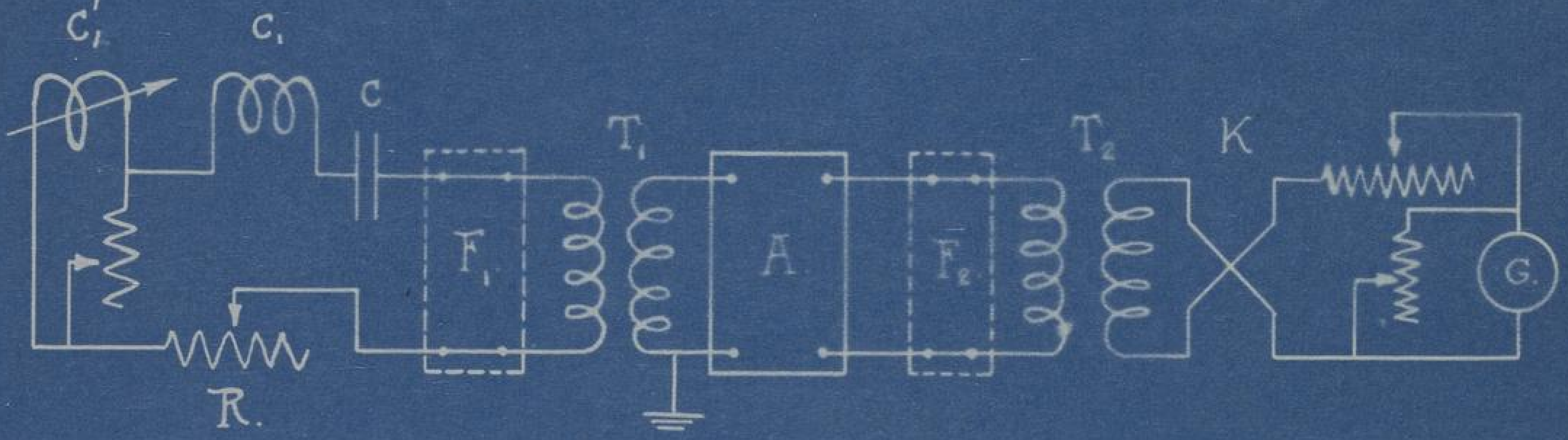
The submarine model was mounted on a small wooden truck rolling on a graduated wooden track, thus permitting approach of the submarine to the detecting coil and magnet, and measurement of the distance at which a standard signal of detection was received in the detecting instrument G.

Scale- 1" = 8'.

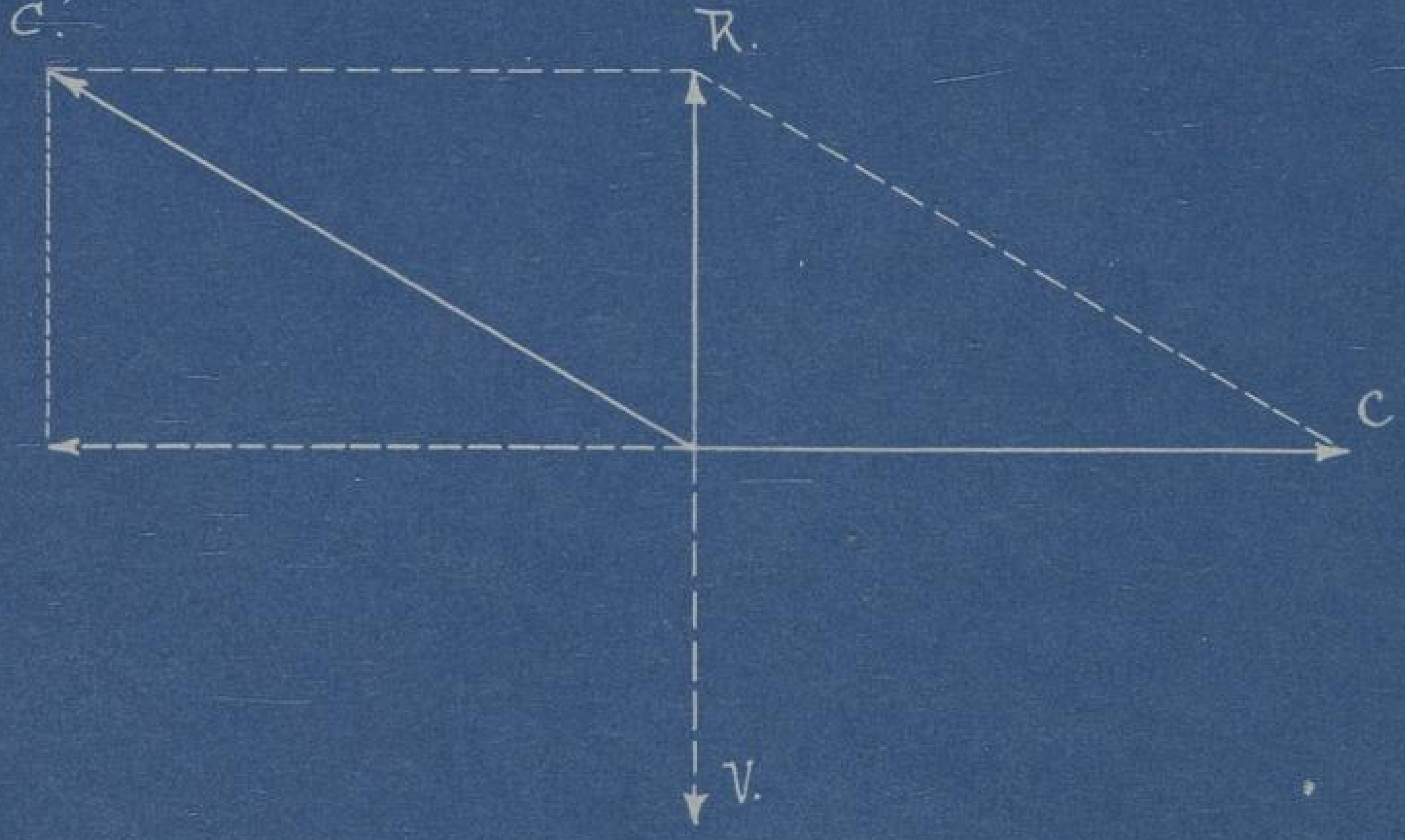

Relative Positions "A".

Relative Positions "B".

Fig. 1.
Laboratory Tests.



~ Elements of Detecting Circuit. ~



E.M.F.'s of Detecting Circuit.

Fig. 2.

Submarine models of other dimensions and characteristics were used at various times and for purposes which will be explained elsewhere.

THE MAGNET M_1.

The magnet had a laminated iron core 6 ft. long and 8.81 sq. in. (66.8 sq. cm.) cross section. The core was bolted together and wedged in a piece of 4 in. internal diameter fibre conduit, over the outside of which the exciting winding was placed.

The exciting winding consisted of 28 coils, each having 52 turns and all connected in parallel. The coils toward the poles had a progressively increasing cross section of copper. The total length of the winding was 69 in.,thus leaving a polar extension of the core of 1.5 in. at each end. The object of this method of winding was to maintain the flux in the core uniform over approximately its full length, thus increasing the effective length of the magnet. For further description of the magnet and its characteristics see Appendix A and Fig. 7.

At 30 cycles the magnet absorbed 200 amperes at 22.6 volts, i. e., 4.52 K.V.A. The power factor was .2 . This excitation was used in the tests described below.

THE DETECTING AND BALANCING COILS.

The detecting coil C_1, used in the final experiments, had the following characteristics:

Outside diameter	9.5 in.
Inside diameter	5.75 in.
Mean diameter	7.625 in. (.635 ft.)
Axial length	1.25 in.
Volume	.0325 cu. ft.
Number of turns	2000
Resistance	70 ohms
Inductance	1 henry

The balancing coil C' had 306 turns of #14 B. & S. wire and its dimensions were the same as those of the detecting coil.

As indicated in Fig. 2, the detecting and balancing coils are connected in series. The electromotive forces in the two coils are in opposition and the purpose of the balancing coil C_1' is to counterbalance exactly the electromotive force induced in C_1 by the field of the magnet. In this condition there is no current in the detecting instrument and an incoming submarine upsets the balance, causing a current in the detecting circuit and detecting instrument. Obviously, if C_1' is placed relatively near the magnet, it need have fewer turns relative to C_1. In this way the countersignal in C_1' due to the magnetised submarine is reduced to a negligible value.

THE GENERATOR.

The generator was a 50 K.V.A., 240 volt, single phase, 60 cycle machine, direct connected to a 240 volt, D. C. compound wound motor. The preliminary experiments having shown that the method was most sensitive at frequencies near 30 cycles, it was necessary to drive this machine at half speed. This was done by reducing the voltage on the motor armature running the fields of both motor and generator at approximately full excitation. The capacity of the generator was therefore reduced to the neighborhood of 25 K.V.A. This figure of capacity is far above that mentioned above for the magnet but it was planned to use this generator for the larger equipment to be used in the later experiments.

Mounted on one end of the shaft of the generator was the commutator for rectifying the signal delivered to the direct current detecting instrument G, Fig. 2. This commutator was carefully constructed. It had six segments corresponding to the number of poles of the generator and the segments were separated by very narrow mica insulation which with narrow brushes permitted very close adjustment of the brushes with reference to the zero of the alternating current.

Worm and gear fitting for the brush holder aided in this accurate adjustment.

The shaft of the generator also carried a second commutator, used in the method of speed control described in Appendix D. It developed in the course of the work that extreme constancy of speed is very essential to high sensitivity of the equipment. (See Appendix G). In Appendix D description is given of two methods for maintaining constant speed.

THE DETECTING CIRCUIT.

The simplest arrangement of the detecting circuit consists of the detecting and balancing coils, and the detecting instrument with its commutator all connected in series. With this arrangement it is possible to obtain a good balance of the system, but the distance of detection is quite small. With a detecting instrument of a given sensitivity, the distance of submarine detection can be increased only by increasing the size of M_1 and C_1. The tests with these simple elements of equipment and the computation in connection with them, given below, indicate that an increase of the distance of detection by this means soon involves prohibitive sizes and weights for M_1 and C_1.

It is therefore important that the sensitivity of the detecting instrument be increased so that signals corresponding to greater distances of the submarine may be detected. However great sensitivity in the instrument itself usually means delicate construction and a thread suspension and these are not suitable for use on shipboard.

Fortunately, it is now possible in effect to increase the sensitivity of a rugged type of instrument to figures which are quite beyond those pertaining to the most delicate laboratory instruments. This may be accomplished by the use of amplifier or pliotron tubes,

now in common use in telephony, telegraphy and radio transmission. The properties of these tubes are now well understood and they need not be described here. They serve in effect as a relay, in which extremely small amounts of energy in the form of electric signals may be used for liberating correspondingly greater signals from a local circuit, and transmitting them to the detecting instrument. The combination of amplifier and detecting instrument therefore results in a sensitivity far beyond that of the instrument alone, so that a rugged and substantial type of instrument may be used - a very important feature for service on shipboard.

The diagram of Fig. 2 indicates the position of the amplifier. Two of these were used during the course of the experiments, one of five tubes or stages and another of four stages. Each was designed by its manufacturer to meet the conditions obtaining in the detecting circuit. They were arranged so that one or more stages might be used at will. A complete description of the two amplifiers will be found in Appendix C.

It will be noted from Fig. 2 that transformers are inserted in the detecting circuit at each end of the amplifier. These transformers were for the purpose of adapting the characteristics of the amplifier to those pertaining to the detecting circuit and to the detecting instrument respectively. The maximum signal for a given disturbance in the detecting circuit will be received in the transformer if the inductive reactance of the detecting circuit is neutralized, and the resistance of detecting coil and transformer are equal. The total voltage generated is then divided equally between the detecting circuit and the circuit to which it is connected. The same considerations apply to the output circuit of the amplifier in its relation to the detecting instrument. The transformers are for the purpose of

introducing receiving and delivery circuits of impedances approximately equal to those pertaining to the detecting circuit and detecting instrument respectively. The reactance of the detecting coil, balancing coil and transformer primary is balanced out with the capacity C by simple experimental adjustment.

In some of the experiments filters, consisting of combinations of resistance, inductance and capacity, for cutting out disturbing frequencies above 30 cycles, were inserted at either end of the amplifier and between the stages of the amplifier itself. These filters are described in Appendix G.

THE DETECTING INSTRUMENT.

As has been already stated, the most suitable detecting instrument is one of the continuous current type. In efforts to introduce the greatest sensitivity by means of the instrument, other types have also been used, as for example, the Einthoven string galvanometer, a high sensitivity electro-dynamometer and sensitive suspension types of D'Arsonval galvanometer. These instruments are in general unsatisfactory by reason of their delicate construction. Not only does this construction render them unsuitable for use on shipboard, but the circuit in which they are connected contains the coils C_1 and C_1', in each of which a very large electromotive force exists. During the process of balancing, there is frequently liberated in the detecting circuit an electromotive force of magnitude far beyond that of the signal to be detected. With an instrument of delicate suspension extreme caution is necessary to avoid disastrous consequences. The most satisfactory type of instrument, as developed by experience, has been found to be a direct reading, needle type, double pivot D'Arsonval galvanometer with zero in the centre of its

scale. The instrument most used in the present experiments was of this type and had a sensitivity of 10^{-6} amperes per millimeter of scale. It had a scale of 25 millimeters on each side of the zero position. The resistance of the instrument was 100 ohms and the critical damping resistance 90 ohms.

Other detecting instruments are described in Appendix B.

THE EXPERIMENTS.

The principal problem in the taking of observations is to secure and to maintain an exact balance of the electromotive forces set up in the coils C_1 and C_1'.

It has been found by separate experiment that the phase of the signal received from the submarine is practically coincident with that of the main magnetic field due to the magnet. The brushes of the commutator, therefore, must be set so as to correspond with the electromotive force induced in C_1 by the main magnetic field. This is readily accomplished by cutting out C_1' and inserting enough resistance in the detecting circuit to insure that the resulting current is in phase with the electromotive force and at the same time that the current in the detecting instrument is within its capacity. This being done, the brushes may be adjusted for zero deflection of the measuring instrument, when the signal will be cut up into an equal number of positive and negative parts. A shift of the brushes by 90 electrical degrees will now bring their setting to the point corresponding to the maximum signal due to C_1 alone.

The problem of the balance is to introduce from C_1' an electromotive force exactly equal in magnitude and opposite in phase to that in C_1. Unfortunately the phase of the magnetic field in the neighborhood of the magnet differs appreciably from point to point. It is relatively easy to find a position in which the value of the electromotive

force in C_1' is equal in magnitude to that of C_1, but quite difficult to find a point at which the phases are exactly the same as between the two coils. This is the most difficult of all the problems which have arisen in these and the later experiments. An extensive series of investigations have been made on the method of balancing, and these are described in Appendix G. In the laboratory experiments here described, by a system of cut and try a position for C_1' was found, in which the phase of the field was exactly coincident with that of C_1. This position being found, it is a relatively simple matter to rotate C_1' about a vertical axis so as to vary the magnitude of its electromotive force until it is exactly equal to that in C_1.

The degree to which the equality of both magnitude and phase of the two opposing electromotive forces is obtained is measured by the constancy of the zero position of the pointer of the galvanometer. If they are not in phase slight changes of frequency will cause sharp upsets of the balance (Appendix G). Naturally it is more and more difficult to obtain a balance the greater and greater the degree of amplification that is used. In fact the limit of sensitivity of the whole apparatus is found by increasing the number of stages of amplification. With increasing amplification the wandering or jerks of the needle about the zero position become greater and greater and more and more irregular until finally they will mask the deflection due to the incoming signal. These disturbances of the balance are largely associated with variations of the speed. The greater the refinement in the control of the speed, the greater the degree of amplification which may be used, and consequently, the greater the sensitivity of the apparatus and the greater the distance of detection.

In the readings given below, the number of stages of amplification used and also the general conditions as to the balance, in terms

of the magnitude of its variation about the zero position, are given in each case. Having obtained a satisfactory balance, the submarine is brought up toward the detecting coil and magnet until a standard signal is received, the distance from the magnet being observed. Throughout the experiments the distance of detection was measured between the centres of the magnet and the submarine. The readings are repeated sufficiently often to be certain of the distance of detection. The standard signal in these experiments was 15 millimeters of scale with a zero disturbance not greater than plus or minus five divisions. In general a ratio of signal to zero disturbance, 3 to 1, has been adopted throughout the experiments.

EXPERIMENTAL RESULTS.

The first results given below pertain to experiments using the detecting coil, balancing coil and measuring instrument alone; that is, no amplifier was used for increasing the sensitivity. The galvanometer however was of the D'Arsonval suspension type, wall mounted, with observation by telescope and scale. This instrument is more sensitive than the needle type galvanometer referred to above:

Tests without Amplifier. Tests of Sept. 4, 1917 - (no amplifier).

Magnet M_1, induction 7200.

C_1 = 2000 turns, C_1' = 8 turns on M_1.

No amplifier, no transformer.

Submarine S_0. Axes of M_1, C_1 and S_0 parallel and in the same plane; (arrangement A). D = 24 in.

Galvanometer: Suspension type D'Arsonval, sensitivity 83 megohms.

Balance: Fair, zero ± 3 mm.

Distance d, measured between centres of M_1 and S_0.

Distance d, feet	Galvanometer readings, cm.						Average Deflection
40	.5	.45	.35	.1	.85	.4	
15	.32	.5	.2	.5	.75	.65	
12	.9	.7	.55	.7	1.3	.7	.36
10	1.7	1.55	1.15	1.4	1.76	1.55	1.05
8	5.5	4.35	4.35	4.35	4.7	4.7	4.6

It will be observed that at a distance of 10 feet between centres of submarine model and magnet, the deflection on the galvanometer was 1 cm. This represents the best result obtained with the simple elements used. It will be taken as a basis for computing the results to be expected with larger apparatus and an actual submarine.

Tests with Amplifier. The following tests are typical of a large number which were obtained using transformer and amplifier for increasing the sensitivity. Many observations were taken and the most reliable are summarized in Table 1. Those quoted below are taken as conservative, having in mind that the condition of balance shown by the behavior of the galvanometer needle is most important as bearing on the reliability of the results. By the use of greater amplification and conditions of greater sensitivity in galvanometer circuit, still greater distances of detection were obtained. As, however, the conditions of the balance were unstable, due to disturbances which could not be recognized and which it was not possible to control, these results obviously cannot be used.

Tests of July 1st and 7th, 1918 - (with amplifier).

Magnet M_1, Induction 3300.

C_1 = 2000 turns; C_1' = 306 turns.

Amplifier: 3 stages with output and input transformers.

DATE.	VOLTS.	AMPS.	"D."	Distance of Detection.	← Galvanometer →			amp'f'r. Stages	Balance Zero.
					Deflect'n.	Shunt R.	Series R.		
1918. 6-26	32	250	26 ft.	50 ft.	20	10	100	4	± 10.
	32	250	26	45	10	10	1000	4	± 5.
				42	25				
	32	250	26	46	15	10	500	4	± 5.
				43	25				
	32	250	26	43	10	10	1000	4	± 2
	32	250	26	46	15	10	0	4	Very Fair.
				42	30				
	32	250	26	44.5	7	90	0	4	Excellent.
				43	10				
				42	15				
6-27	23	175	26	44.5	5	10		3	± 1.
				43.	8				
				42.	10				
	13	100	26	43	6	10		3.	± 1.
				40	12				
	5	42	26	40	5	10		3.	± 1.
				37.5	11				

Table 1. Summary of Detection Tests in Laboratory.

DATE.	VOLTS.	AMPS.	"D."	Distance of Detection	← Galvanometer →			Amp'fr. Stages	Balance Zero.
					Deflect'n	Shunt R.	Series R.		
6-27	32	250	26 ft.	45 ft.	10 to 15	10		5	± 5.
	32	250	26	47 to 52.		10		4	Poor.
	32	250	26	48	5	10		3	± 1.
				46	8				
				44	10				
6-28	13	100	26	48		10	200	4	± 10.
				47					
7-1	13	100	26	52	10	10		4	± 10
				48	15				
7-3	13	100	26	44	15	90		3	± 3
				42	25				
7-6	13	103	26	50	3	90		3	± 2.
				47.5	5				
				44	12				
				42	25				
				51.5	5	10		4	± 7
				50	10				
				48	18				
				47.	25				

Table 1. Summary of Detection
- Tests in Laboratory. -

Submarine S_0, axes of M_1, C_1 and S_0 in the same straight line (arrangement B). D = 26 ft.

Galvanometer: S. and H. with 90 ohm shunt, sensitivity 5 x 10^{-5} amps. per div.

Balance: Very good, zero ± 2 div.

Distance d, measured between centres of M_1 and S_0.

Observations:

	scale divisions	
D = 42 ft.	25	25
44 ft.	12	15
45 ft.		8
46 ft.	5	

It will be observed that the maximum distance at which detection of the submarine was noted were between 42 and 46 ft.

OTHER LABORATORY DETECTION TESTS.

A large number of other detection tests were conducted in the laboratory. The more important of these bore upon such questions as the relative position of submarine and magnet, the influence of variation in the dimensions of the submarine, etc. An investigation of special interest was that looking toward the use of the steel hull of the searching vessel as the magnet. Accounts of some of these tests are found in the appendices.

POSSIBLE DISTANCE OF DETECTION AS ESTIMATED FROM LABORATORY TESTS.

The results of the laboratory tests may be made the basis of a computation of the distances of detection to be expected with enlarged equipment and the full sized submarine.

The magnetic field strength of intensity due to a bar magnet at a point on its axis is

$$f = \frac{2M}{d^3} \qquad (1)$$

and at a point on a line normal to the axis and passing through the centre of the magnet

$$f' = \frac{M}{d^3} \qquad (2)$$

where M is the moment of the magnet and d is the distance of the point from the centre of the magnet; d is assumed to be large compared with the length of the magnet.

Let l_1 and a_1 be the length and diameter of the core of the magnet M (Fig. 1); l_2, a_2, t_2 and V_2 the length, mean diameter, radial thickness and volume, respectively, of the detecting coil C_1; and l_3, a_3 and t_3 the length, diameter and thickness of shell, respectively, of the submarine.

Let the magnetic field intensity at S due to M be f_1, then in either arrangement of Fig. 1, if the magnetic flux density in the core of M has always the same value

$$f_1 = K_1\frac{l_1 a_1{}^2}{d^3} \qquad (3)$$

also the field intensity at C_1 due to S will be

$$f_2 = K_2 f_1\frac{l_3 a_3 t_3}{(d-D)^3} \qquad (4)$$

This assumes that the whole length of the submarine is subjected to the same magnetic intensity and that the resulting flux is proportional to the cross section of its skin, that is, to the product of its mean diameter and the thickness of its plates. These assumptions are obviously open to question, but they are approximately correct when d is large compared with l_1 and l_3. Experimental studies of this relation, particularly for values of d comparable with the length of the submarine, are given in Appendix F.

The electromotive force induced in the detecting coil will be proportional to f_2 and will also depend upon the dimensions and number

of turns in the coil. The signal on a given detecting instrument will be a maximum when the resistance of the detecting coil is equal to that of the instrument and when the reactance of the coil is completely neutralized. We will assume then that the resistance R of any larger detecting coil will have the same value as that of the coil used in the above experiments. This value was approximately equal to the resistance of the detecting instrument used. We have then if l is the axial length, t the radial depth, a the diameter, and n the number of turns in the coil C_1

$$R \propto \frac{\pi a n}{\frac{lt}{n}} = \text{const} \tag{5}$$

$$\therefore \quad n = K\sqrt{\frac{lt}{a}} \tag{6}$$

The e.m.f. in the detecting coil e is

$$e = k_1 a^2 n \tag{7}$$

$$= K_2 a^2 \sqrt{\frac{lt}{a}} \tag{8}$$

$$= k_3 a V_2^{1/2} \tag{9}$$

Thus the e.m.f. or signal in the detecting coil due to the magnetic field f_2 set up by the submarine will be

$$S = K_1 K_2 K_3 \frac{l_1 a_1{}^2 a_2 V_2{}^{1/2} l_3 a_3 t_3}{d^3(d - D)^3} \tag{10}$$

and if an arbitrary constant signal in the detecting instrument be selected, the distance of detection for any magnet, coil and submarine is

$$d = \frac{D}{2} + \sqrt{K(l_1 a_1{}^2 a_2 V_2{}^{1/2} l_3 a_3 t_3)^{1/3} + \frac{D^2}{4}} \tag{11}$$

By substituting in the above expression the dimensions of the magnet, detecting coil and submarine model, used in the experiments described above, the value of K may be found and d may then be computed for any size of magnet, coil and submarine by substituting the proper values for l_1, a_1, a_2, etc. Obviously in this method of computing d it is assumed that the magnetic flux density in the core of the large

magnet is the same as that in the core of the small magnet M_1 used in the experiments.

In the above development, no account has been taken of the signal in the balancing coil C_1'. In all of the experiments the number of turns in this coil has been small compared with the number in the detecting coil and its area has also been relatively small. In order to obtain the value of electromotive force necessary to balance that in the detecting coil, it has only been necessary to place the balancing coil nearer to the magnet. Simple computation shows that in all the experiments the countersignal in the balancing coil C_1' due to the submarine was in all cases negligible compared with the main signal in C_1.

In the two sets of experimental observations given above, one using no amplifier and one using amplifier and transformer, one covers the arrangement A, in which the axes of the magnet, coil and submarine are parallel to each other, and the other the arrangement B, in which these three axes are in the same straight line. The magnetic intensity for a given distance from the centre of the magnet is greatest at points on its axis, consequently we should expect greater distances of detection when the axis of the submarine coincides with the axis of the magnet and this has been borne out by the experiments. The development of the formula for the distance of detection, as given above, follows the same steps and takes the same form for either relation between submarine and magnet. The only difference in the two cases will lie in the different values of the constant K, consequently we shall remember in predicting distances of detection that the values arrived at will pertain to the particular relative position of submarine and magnet which were used in the experiment forming the basis of the computation. Results for arrangement B may be computed from tests with arrangement A by inserting a factor 4 inside the bracket of

formula (11), see page 28 and Appendix F.

Substituting the figures for the dimensions of the apparatus used in the tests of September 4, 1917, using the foot as the unit of length and noting that the distance of detection was 10 ft. for a standard signal of 1 cm., we obtain for the constant K in formula (11) the value 31.3. This pertains to the simplest elements of the apparatus, that is, no amplifier being used. This value may therefore be used in formula (11) for computing the distance of detection d corresponding to any larger magnet, detecting coil and submarine.

A submarine of recent type may be assumed as having a length of 200 ft., average diameter of 20 ft. and a thickness of skin .03125 in. One or two approximate trials with formula (11) will show that in order to obtain even moderate distances of detection, quite large sizes of both magnet and detecting coil will be necessary. For example, with a magnet 25 ft. long and core 1 ft. in diameter and a detecting coil 10 ft. in diameter and 9 sq. in. cross section, and a distance between magnet and coil, D, of 50 ft., the distance of detection is only 185 ft. Bearing in mind the equipment necessary to excite so large a magnet and the space requirements for the magnet and coil, it will be seen that the device promises little value unless the magnitude of the signal can be greatly increased, thus permitting a smaller size and mass of equipment.

The outlook is somewhat improved when we come to the tests of July 1st and 7th, 1918, reported above, in which the amplifier was used. Again making the substitutions in formula (11) and taking the distance of detection as 44 ft., corresponding to a scale deflection 12 to 15 divisions, we find the value of K to be 7730. Substituting this value in formula (11), the distance of detection for the magnet 25 ft. long, the detecting coil 10 ft. in diameter and the submarine 200 ft. long,

is 557 ft. As stated above, however, a coil and a magnet of such sizes could hardly be used. With a magnet 16 ft. long and .91 in. in diameter and a detecting coil 7 ft. in diameter and 9 sq. in. radial cross section, both of which were subsequently constructed, and with a distance between them of 70 ft., the distance of detection as computed is 467 ft.

Considering the possibility of extending the experiments to enlarged apparatus and a full size submarine when submerged it may be noted that the relative location of magnet, coil and submarine, as shown for arrangement A (Fig. 1) might be maintained on a searching vessel by placing the magnet on deck and the detecting coil in the bottom of the vessel. Retaining the relative position of magnet and coil in the same horizontal plane as in arrangement A, the distance of detection for a submarine directly beneath the vessel will be only slightly less than that for a submarine dead ahead of the detecting vessel and on the surface, the relation used in the laboratory tests.

Referring to arrangement B, in its relation to observations on an actual submarine, the tests and computed distances would strictly apply only to a submarine whose axis coincided with that of the magnet and coil. A number of observations were actually taken with this arrangement after going on shipboard, but owing to the large values of e.m.f. in the detecting coil, the conditions of balance were not as satisfactory as with arrangement A. In the laboratory tests arrangement B was used, since of all the various arrangements of relative location of magnet, coil and submarine, it gave the greatest distance of detection and upon this maximum distance there depended decision as to whether the experiments were to be carried further. A direct comparison of the relative distances of detection, using the two arrangements A and B is described in Appendix F and

they show them to be in approximately the ratio 1 to 1.37. This agrees roughly with theory. It will be noted that the method of deduction of the formula giving the distance of detection applies equally for the two arrangements A and B. The constants K_1 and K_2 however for the arrangement B have twice their values for arrangement A. As these constants enter the final expression for the distance, we would expect the distances of detection, as between arrangement B and arrangement A to be approximately as the one-sixth root of 4, that is, 1.26. As stated, the experimental results bear this out approximately. We may therefore safely use the results given above for arrangement B as a basis for the prediction of a distance of detection of 377 ft. with the magnet 16 ft. long and the coil 7 ft. in diameter, described above, when the equipment is assembled for arrangement A and when three stages of amplification are used.

EXPERIMENTS AT ANNAPOLIS.

Particularly favorable conditions were found at the Engineering Experiment Station, Annapolis, for conducting some intermediate tests on actual steel hulls of full size, without the necessity of diverting from other purposes a vessel on which the detecting apparatus would be assembled. In view of the uncertainty as to what bearing the character of the hull of a steel vessel would have on the results it was deemed advisable to undertake experiments with enlarged magnet and coils and the use of steel hulls approximating those of the modern submarine, before going to the more elaborate and expensive equipment necessary on shipboard.

The detecting coil, magnet, motor generator, etc., were assembled on the end of a pier reaching into deep water and well removed from possible disturbing influences. The Experiment Station also offered complete facilities for the construction and assembly of much of the necessary equipment. Electric power was also available in ample quantity.

In order that all factors entering might be made as large as consistent with their convenient usage, and so increase the maximum distance of detection, it was determined to build a magnet with the largest possible moment with an excitation of 26 K.V.A., the limiting capacity of the available motor generator set. This magnet which we will call M_2 had an effective length of 16 ft. and an overall diameter of approximately one foot. Its weight mounted on its base was 4000 lbs. A complete description of this magnet is given in Appendix A.

The detecting coil, C_2, constructed for these experiments had a mean diameter of 7 ft. and a winding cross section 3 in. x 3 in. It contained 1307 turns and had a resistance of 60.7 ohms and an inductance of 8.22 henrys. Its total weight mounted in its frame was 1500 lbs.

The balancing coil, C_2' was 3 ft. in diameter with a winding cross section 2 in. x 2 in. It had 530 turns and 9.86 ohms resistance. This coil was adjustable about a diameter arranged as a vertical axis. Its exact position could be accurately controlled and set by means of a worm screw and gear. Its weight in its mounting was 525 lbs.

The motor generator set with its speed control equipment, used in the Johns Hopkins University tests was also used at Annapolis. In all other particulars, as regards amplifier and other auxiliaries, the apparatus was assembled and operated in the same manner as pertained to the Baltimore experiments.

The vessels on which detection tests were made were the ocean tug "Standish" and the converted yacht "Wasp". Their respective dimensions are as follows:

Standish: Length overall, 150 ft.
Beam, 27 ft.
Depth, 11 ft. (from deck to keel)
Skin, wrought iron 1/2 in. thick
Wooden deck on steel frames 18 ft. apart.

Wasp: Length overall, 203 ft. 9-1/2 in.
Beam, 23 ft.
Depth, 18 ft. (from rail top to keel)
Skin, steel 5/8 in. thick with additional armour belt amidships 55 ft. long, 6 ft. wide and 1 in. thick.

As shown in Figure 3, the pier at the Experiment Station projected toward deep water and had a deck or basin alongside. The detecting coil was set up on the extreme corner of the pier and the magnet placed in various relative positions. The balancing coil was shifted to various convenient positions in relation to the magnet, and close to the balancing coil a small observing platform, protected from the weather carried the detecting instrument and balancing equipment. (See Appendix G). The amplifier and the motor generator for exciting the magnet were located nearby in the Station, permitting ready access for commutator setting, speed control, inspection of amplifier, etc.

OBSERVATIONS.

In taking observations a satisfactory balance of the detecting instrument was first obtained. A wig-wag signal was then sent to the vessel to approach on a prearranged course. Her position at all times was observed by a simple system of triangulation, as indicated in Figure 3. When the signal was received on the detecting instrument the observer near the balancing coil signalled by means of a bell and the position of the vessel was thus noted at the corresponding moment. A corresponding signal was generallytaken as the vessel withdrew. Owing to the size of the vessels and the difficulty of maneuvering at slow speed and in the neighborhood of shoal water, it was not always possible to approach accurately on a prearranged line. Figs. 3, 4 and 5

8-14-18. "Wasp" Tests. Excitation M : 19.6 KVA.

~ Runs #1, 2, 3, and 4 with 3 stages and transformer. ~
Run #5 with 2 stages and transformer.

Summary.

Run.	Center of M to Center W.	Center of C_1 to Center W.	Center of C_1 to Bow of W.
#1	360. ft.	285.	200.
#2	415.	350.	345.
#3	330.	270.	175.
#4	460.	395.	295.
#5	240.	175.	70.

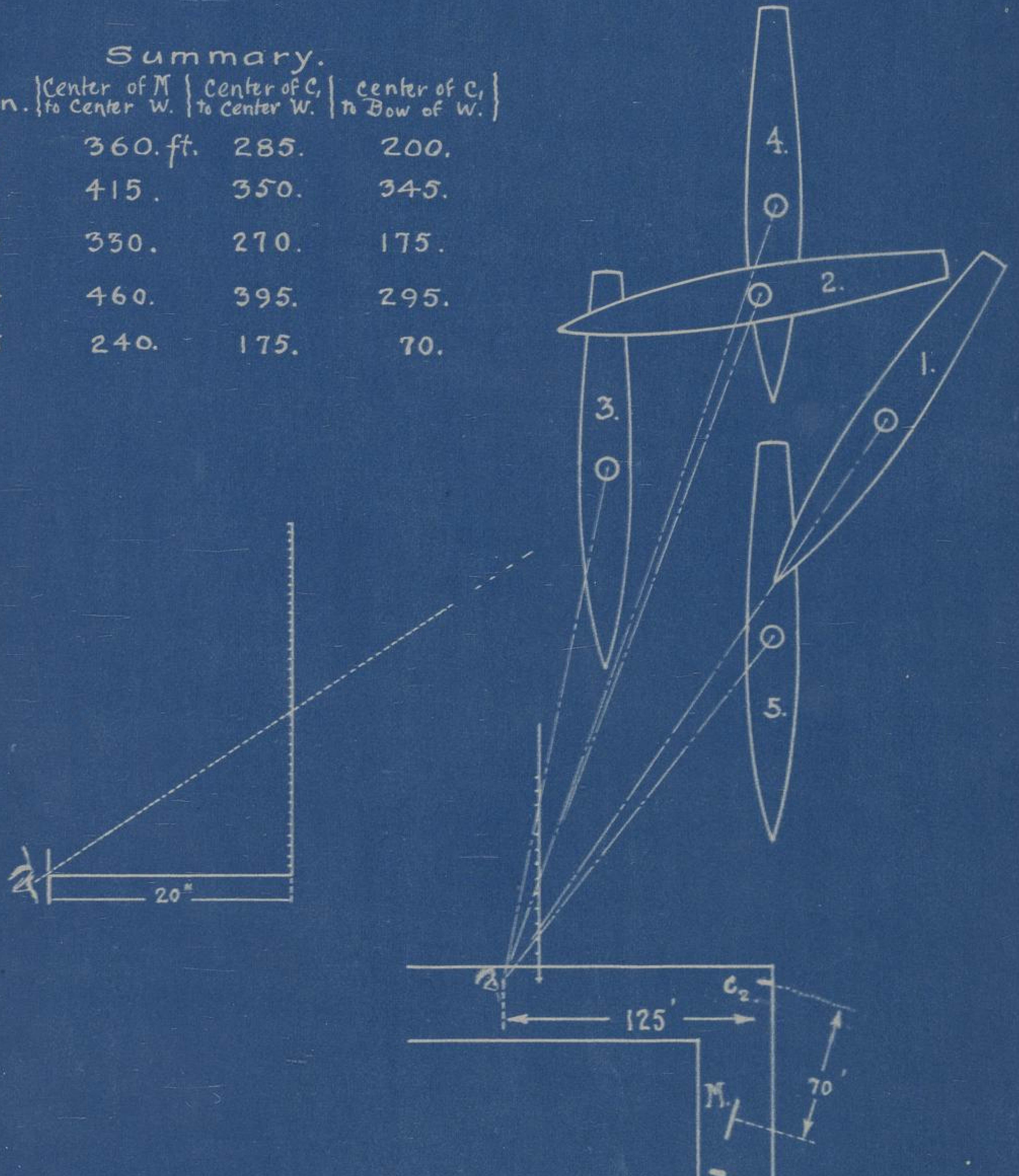


Fig. 3.

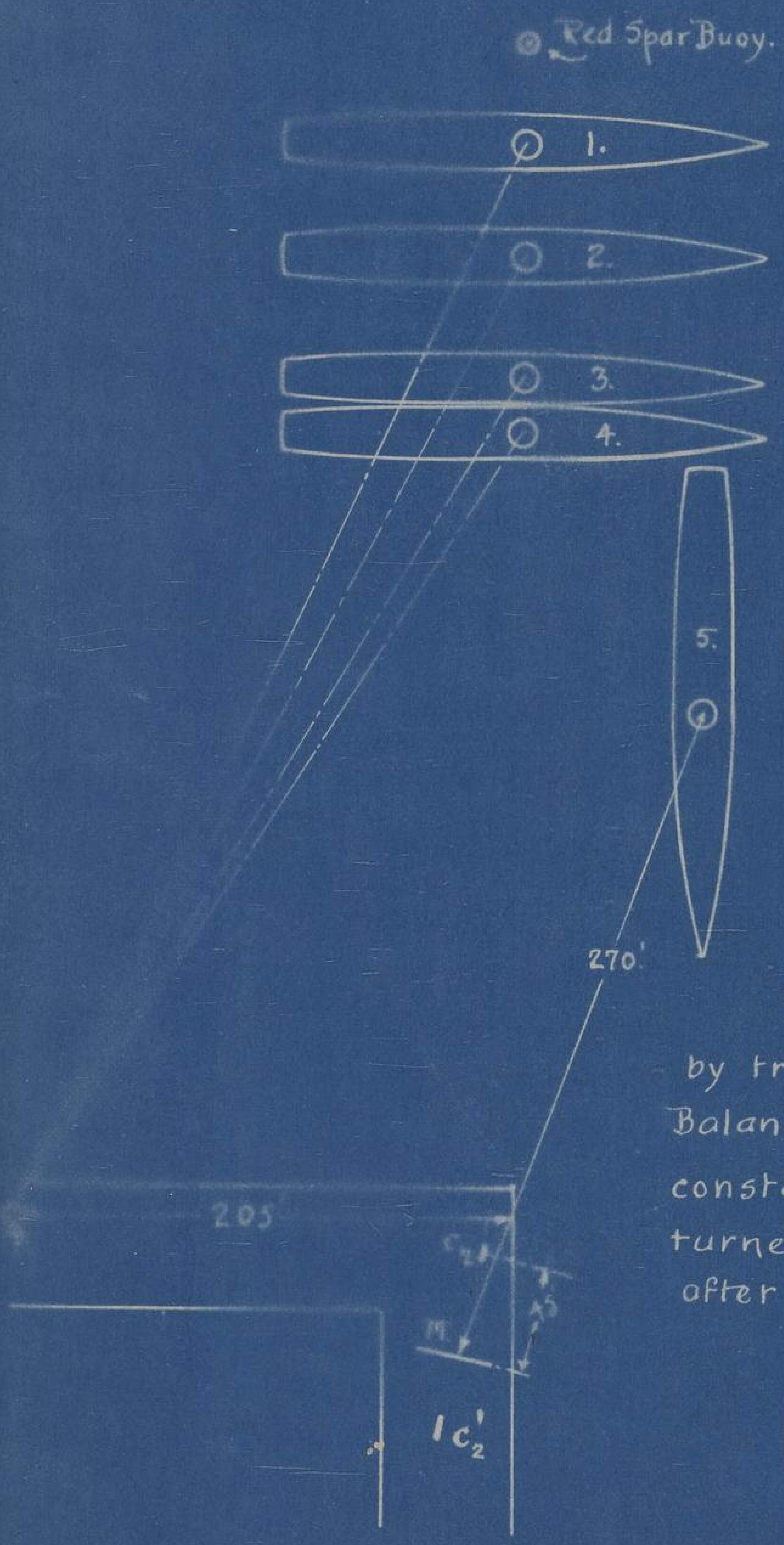
8-16-18. Detection Tests ~ Yacht "Wasp."

M] $\underline{C_2'}$ Large Magnet and Coils.

3 stages and transformer.

10 ohm shunt. Excitation 93 amps; 50 volts;
4.65 KVA.

d = M to Sub. ~ Wasp.
d' = c' to Sub. ~ Wasp.



#1 d = 500 feet. No signal,
or less than 10 div's.

#2. No observations.
Speed out.

#3. d = 392 ft.; d' = 347 ft.
Signal off scale.

#4. d = 370 ft.; d' = 325 ft.
Signal = 20 div'ns.

#5 - in. d = 230 feet.
Signal - "bang off scale."

#5 - out. d = 270 feet.

Signal ~ needle just leaving back stop, and coming on scale.

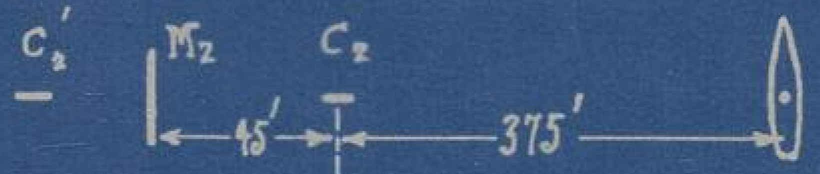
Distances measured by triangulation from point "P". Balance conditions good at constant speed; needle returned to center of scale after all signals. ~

Fig. 4.

8 - 21 - 18.

Detection Tests ; "Wasp". Large Magnet and Coils.

Set commutator with C_2 and C_2' in, C_2' upset for e.m.f., and with 3.15 mf + 12000 w in detecting circuit. M_2 = 94 volts, 165 amperes, 15.5 KVA. Commutator zero at 143°; set at 173°.

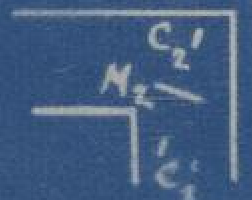


Test #1. 2 stages and transfr.

Signal : 20 divs & return distance 375' c_1 to S, larger signal desirable.

#2. Repeat #1, distance 450', no signal.

#3. Repeat #1, using 3 stages and 10 w shunt. Strong signal before crossing axis, and return some time after. Distance when on axis = 350' c_1 to S., 395 M to S.



#4. Return to 2 stages and repeat. Axis crossed at 400' c_1 to S ; no signal.

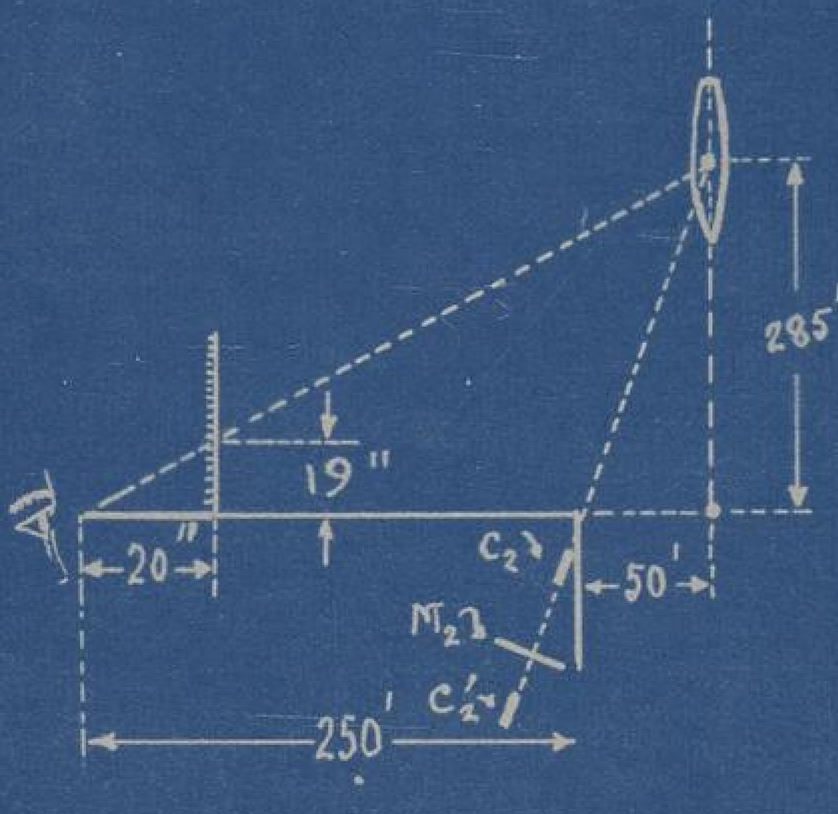
#5. Wasp standing in to center of basin, a little to south of center line, say 50 feet from pier.

2 stages.

Signal ;- off scale and return.

distance C_2 to S - 285 ft.

M to S - 330 ft.



~

~ Fig. 5. ~

give extracts from the daily record and show the conditions in some of the best tests.

A summary of the more important tests is given in Table 2. A number of other tests were taken. The table gives in the first two columns the date and number of the test. The second column gives the magnet used and its excitation at the time of the test. M_1 is the magnet used in the laboratory tests at Baltimore and M_2 is the large magnet especially constructed for these tests, and described in Appendix A. Similarly, for the detecting coil, C_1 refers to the small coil of the laboratory tests and C_2 to the coil 7 ft. in diameter. The Standish and the Wasp are indicated by the letters S and W respectively. The sixth column gives the relative positions of the vessel, detecting coil and magnet; the seventh the distance D from detecting coil to centre of magnet. The succeeding columns give the particulars as to the degrees of amplification and sensitivity of detecting instrument, the condition of the balance, and the magnitude of the signal. In the last, or 13th, column are given the observed distances of detection and also the distances as calculated using the laboratory tests as a basis.

In computing the distance of detection using the laboratory tests as a basis, the dimensions of the enlarged equipment are inserted in formula (11) in the method described. In addition, account had also to be taken of several other important factors. The modifications on account of these several factors are as follows:

Excitation of Magnet. The strength of the pole of the magnet in the laboratory experiments appears in the formulae as the square of the diameter of the core of the magnet, a definite flux density being assumed. The total flux in the large magnet at 115 volts and 30 cycles is known, (See Appendix A), consequently its total flux at any other

No. of Test-	Date.	Magnet and KVA.	Detect. Coil.	Vessel Detected.	Rel. Position. S. c. m.	D feet.	Amplifier Stages.	Galvanometer.	Galvanom Shunt-Ohms.	Balance Condition Div'ns.	Signal div'ns.	Distance of Detection.	
												Obs.	Calc.
1	8-2-18	M_1-4.25	C_1	S.	→ ı —	71	4	S+H.	10	±5	25	196	179
2	8-2-18	M_1-4.25	C_1	S.	→ ı —	71	3	S+H.	90	±2	10	186	161
1	8-14-18	M_2-20.5	C_2	W.	Fig.(3)	70	3	S+H.	10	±10	30	360	396
2	8-14-18	M_2-20.5	C_2	W.	Fig.(3)	70	3	S+H.	10	±10	30	415	396
3	8-14-18	M_2-20.5	C_2	W.	Fig.(3)	70	3	S+H.	10	±10	30	330	396
4	8-14-18	M_2-20.5	C_2	W.	Fig.(3)	70	3	S+H.	10	±10	30	460	396
3	8-16-18	M_2-4.65	C_2	W.	Fig.(4)	45	3	S+H.	10	good.	30	392	272
4	8-16-18	M_2-4.65	C_2	W.	Fig.(4)	45	3	S+H.	10	good.	20	370	272
5	8-16-18	M_2-4.65	C_2	W.	Fig.(4)	45	3	S+H.	10	good.	>30	270	
1	8-20-18	M_2-7.26	C_2	S.	—→ - |	45	3	S+H.	10	±10	30	280	
3	8-20-18	M_2-7.26	C_2	S.	↑ - |	45	3	S+H.	10	fair.	20	410	257
3	8-21-18	M_2-15.5	C_2	W.	↑ - |	45	3	S+H.	10	fair.	20	395	304
5	8-29-18	M_2.-7.1	C_2	S.	→|—	50	2	S+H.	90	±10	30	240	234
1	9-4-18	M_2-11.0	C_1	S.	→|—	50	3	S+H.	90		30	206	215
5	9-4-18	M_2-11.0	C_1	S.	→|—	50	3	Weston.	90	±15	30	214	215
7	9-4-18	M_2-11.0	C_1	S.	→|—	50	2	Weston.	0	±0.5	5	198	190
12	9-4-18	M_1-6.2	C_1	S.	↑ - |	28	3	Weston.	90		10	101	108

Table 2. Summary of Tests on Shore.

voltage is also known. This total flux divided by the total flux pertaining to the laboratory tests will give the area, and consequently the diameter of the large magnet in terms of the laboratory magnet as a unit. In other words, the large magnet may be worked at a very different flux density from the small magnet, but its equivalent effect is expressed in terms of a diameter worked at the same flux density as the laboratory magnet.

Relative Position of Magnet and Vessel. The basic laboratory experiment brings the submarine in on the axis of the magnet. In a number of the present tests the course of the vessel is parallel to the axis of the magnet. (See Fig. 4). In this case, the field at the detecting coil due to the vessel will be only 1/4 that for a corresponding distance when the axes of magnet, coil and vessel are in the same straight line. As explained on page 28, this will result in a factor 1/4 in the bracket under the radical of formula (11).

Effective Length of Submarine. If the axes of the submarine and the magnet are parallel to each other and if the centre of the submarine is on a line perpendicular to the axis and passing through the centre of the magnet, the magnetic field at great distances from the magnet will be practically uniform over the whole length of the submarine. As the submarine is approached to the magnet, however, the field becomes less and less uniform and also changes in direction, tending to become more and more normal to the surface of the submarine. This means that the magnetic poles of the submarine which act on the detecting coil are not located near the ends of the submarine. In other words, the effective length of the submarine as a magnet becomes less and less than its actual length, as the submarine approaches the magnet. This effect becomes especially important for distances comparable with the length of the submarine itself. The matter was

investigated in the laboratory with the 10 ft. model submarine and the results are described in Appendix F. From the curve of figure 22, for example, it will be seen that for a distance equal to the length of the submarine, its effective length as a magnet is only 1/2 the actual length of the model.

Amplification and Sensitivity. In the higher values of excitation of the magnet and shorter distances of detecting coil from the magnet, the electromotive force in this coil has higher values. For a condition of balance the electromotive force in the balancing coil must also be higher and the magnitude of any inequalities of balance are proportionately increased. The result is that a given stability of balance is harder to obtain and in fact it is necessary to work at a lower degree of amplification or lower sensitivity in the detecting instrument in order to obtain a workable balance. Thus, for example, in the laboratory tests quite satisfactory balances were obtained using three stages of amplification and a 90 ohm shunt to the detecting instrument. In the present tests this degree of sensitivity was not possible even for the largest distances of the detecting coil from the magnet. If three stages of amplification were used, the galvanometer shunt was commonly reduced to 10 ohms. Sometimes two stages of amplification with a 90 ohm shunt were found advisable.

The resistance of the detecting instrument was 100 ohms. The resistance of the secondary winding of the transformer connected to the output of the amplifier was 70 ohms. The net amplification per stage of the amplifier was in the neighborhood of 20 times. From these figures it is possible to compute the relative sensitivities of any two sets of values of amplifier stages and galvanometer shunt. In particular, three stages and a 10 ohm shunt to the galvanometer give an amplification 5.6 times that of 2 stages and a 90 ohm shunt.

The factor giving the ratio of any two values of sensitivity must also be carried inside the bracket under the radical in formula (11). Corrections on this account have been necessary in several cases in Table 2.

Diameter of Submarine. The submarine models in the laboratory tests were of circular cross section. Obviously the Standish and Wasp departed radically in this particular. In computing the distance of detection in Table 2, the metal cross section of hull of each of the vessels has been assumed distributed in the form of a circle and the resulting diameter used in the computations. The equivalent diameters so found were 15 ft. for the Standish and 16 ft. for the Wasp. In the case of the Wasp the armour belt has been assumed as distributed uniformly over the surface of the 5/8 in. skin, increasing its thickness to .6875 in. or .0573 ft.

SURVEY OF LAND TESTS.

Inspection of the results of Table 2 will show that the maximum distances of detection were somewhat under 500 ft. and that these were obtained with arrangement B, that is, with the axes of magnet, coil and submarine in the same straight line. Moreover the actual distances of detection are in good agreement with the distances predicted from the laboratory tests.

With the relative position A, (Fig. 1), that is, with axes of magnet, coil and submarine parallel to each other, there is for the most part rather poor agreement between the results as observed and as computed, the observed distances being considerably greater. In fact, in the experiments with the large magnet and coils there is comparatively little difference in the distances of detection as between arrangements A and B. The reduction factor of 1/4 for the field

due to the submarine in arrangement A, indicated by theory and used in computing the distance in terms of the laboratory tests, has apparently been compensated in some way which is not evident.

Other observations, for which there is no direct explanation, are those of test No. 2 on August 14th and test No. 5 on August 16th. From the relative directions of the axes of magnet, detecting coil and vessel it is not obvious why such great distances of detection should be reached.

Table 2 also shows that the excitation of the magnet may be greatly decreased without seriously decreasing the distance of detection. For example, in the tests of Aug. 16th, with an excitation of 4.65 K.V.A. the distance of detection is still 392 ft. With the small magnet and coils of the laboratory tests, and an excitation of 6 K.V.A., the Standish was detected at a distance of 101 ft. with the less favorable relative arrangement A.

Taken as a whole, it may be concluded from these experiments that the approximate method for computing distances of detection with any given equipment, as based on the laboratory tests, is a satisfactory one.

DETECTION TESTS AFLOAT.

The distances of detection reached in the shore tests and the approximate agreement between the experimental and calculated values were deemed sufficiently encouraging to warrant a study of the probable distances which could be reached with equipment on shipboard.

The total weight of the equipment used in the shore tests, 17,000 lbs., was unnecessarily large, even for a magnet of the capacity of M_2. This was principally due to the fact that the motor generator was of higher rating than that of the magnet and no special effort had

been made to limit the weight of several other portions of the equipment. Moreover, tests both in the laboratory and at the Engineering Experiment Station (as, for example, the tests on August 16, 1918) had shown that it was possible to obtain good results with considerably lower figures for the excitation of the magnet. This is in accord with theory, as the distance of detection varies approximately as the sixth root of the total flux emanating from one pole of the magnet. (See formula (11)).

The method requires the use of a wooden vessel. The number of such vessels available, of length greater than 100 or 150 ft., is very limited. The 110 ft. submarine chasers were seen to possess many features advantageous for testing this method. Not only have they wooden hulls, but are driven by three gasoline engines of six cylinders each, and this feature results in extreme steadiness when under way. In addition, it will be seen, from a description below, that the space on board was admirably adapted to the accommodation of the necessary equipment. A study was therefore made as to the maximum equipment which could be installed on one of the chasers, the magnet being limited to the capacity which could be furnished by a 3-1/2 K.W., 120 volt, D. C. gasoline-driven generator, installed on the chaser for pumping and other purposes. As based on tests on shore, it appeared that it should be possible, with this equipment, to reach distances of detection up to 250 ft.

It is obvious that the distances of detection which have been mentioned are dependent strictly upon the degree of sensitivity which is used in the detecting circuit. Throughout the experiments it was always found that in the combination of amplifier and measuring instrument it was possible to obtain figures for sensitivity higher than it was possible to use by reason of the limitations of

the exact balance between the detecting and balancing coils. The many features affecting this balance are discussed elsewhere, but one vital factor is a fixed relation between the magnet, detecting and balancing coils. If any one of the three moves, with reference to the others, the balance is correspondingly upset. It was realized therefore, in going to tests on shipboard, that there was a large chance that the distances predicted might be seriously curtailed, if not entirely lost, by reason of the vibration due to the engine of the vessel and to the straining or distortion of the hull of the vessel due to the motion of the sea. There appeared also a possibility that these factors might have an influence on the delicate relations obtaining in the amplifier tubes and on the detecting instrument. However the unusual steadiness of the submarine chaser, as regards her engines, seemed to offer exceptionally favorable conditions in this respect. Moreover, a promising method of spring suspension for the amplifier and a robust detecting instrument which seemed to be independent of moderate motion also gave promise of partially avoiding the difficulties mentioned in connection with these instruments. It was therefore decided to construct and install the equipment, described below, on Submarine Chaser No. 326, stationed at Annapolis, and placed at the disposal of the Naval Consulting Board at the request of the Special Board of the New London Naval Experimental Station.

SUBMARINE CHASER NO. 326.

The "S. C. No. 326" is 110 ft. long, 15 ft. beam midships and has an average depth from deck to keel of about 10 ft. She is of wooden construction throughout except that she has six water-tight, steel bulkheads. Other metal masses are the engines, propeller shafts, rudder, ventilators, air and gasoline tanks, anchor, stanchions, deck

posts, etc. Outline drawings of elevation and deck plan, shown in Fig. 6, indicate the construction of the vessel and the relative location of her equipment, the steel bulkheads, and the experimental apparatus.

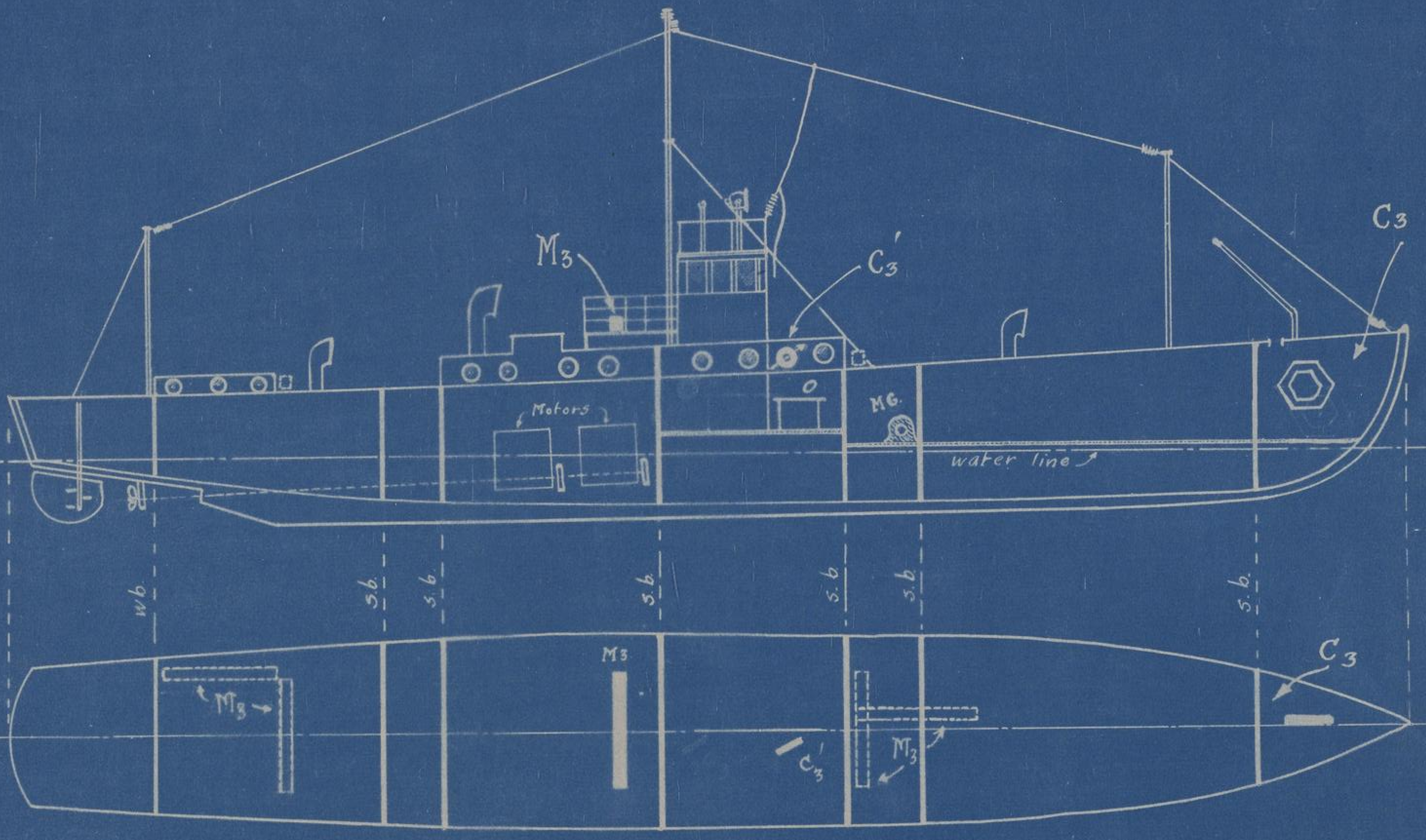
The earlier experiments had shown that the proximity of masses of metal had no effect on the balance conditions so long as these masses were stationary. Several rough experiments were made in order to determine the influence of such masses and no striking influence was found. It was always possible to secure practically the same conditions of balance when the metal mass was present or absent.

It was recognized, however, that the steel bulkheads of S. C. #326 offered a condition which had not been considered in the earlier work. These bulkheads, stretching the full width of the ship, are longer than the magnet and no positions for the magnet can be found which are very far removed from some one of these bulkheads. The influence of the bulkheads therefore was an uncertain factor. Subsequently, a number of experiments were made to determine this influence and it was found that the phase of the magnetic field near the bulkheads was markedly affected by them, that the influence on the balance could be eliminated, while the influence on the sensitivity, while appreciable, was not great.

THE MOTOR GENERATOR.

The generator was a 5 K.V.A., single phase, 60 cycle machine, direct connected to a 220 volt, compound wound, D. C. motor, operated at full excitation and half voltage, thus driving the set at one-half speed for 30 cycles. The power for the set was supplied by the 3-1/2 K.W. gasoline auxiliary set, already described, which was located in the engine room. The motor generator, together with all of its control equipment, was located in the magazine, as indicated at MG, Fig. 6.

Scale - 1" = 12 Feet.



Submarine Chaser, "S.C. 326."

~ Fig. 6. ~

{s.b. - steel bulkhead.
w.b. - wooden bulkhead.}

On one end of the shaft was located the rectifying commutator of the detecting circuit. The other end was equipped with special control devices, including ball thrust bearings, for constant speed, as described in Appendix D. There is no more important feature for a balance of high sensitivity in the detecting circuit than constancy of speed. Much time and effort were devoted to perfect the two speed control methods described in Appendix D and it is believed that a high degree of perfection was attained.

THE MAGNET M_3.

The core of the magnet was 9 ft. long and had a cross section of 7.7 sq. in. (49.5 sq. cm.). The core was placed inside a piece of 4 in. internal diameter fibre conduit, over the outside of which the exciting winding was placed. This winding consisted of six similar one layer coils of 104 turns each, No. 10 B. & S. cotton covered wire, all connected in multiple. The length of the core beyond the winding at each end was 15 in. The magnet was mounted in a suitable wooden frame and housing. Other particulars concerning the magnet will be found in Appendix A and Figure 8.

In Figure 6 the magnet is shown as located on the bridge of the chaser just abaft the pilot house. Other positions in which observations were made are indicated in dotted line on the deck plan.

THE DETECTING AND BALANCING COILS C_3 and C_3'.

Two features are desirable for the location of the detecting coil; one that it should be below decks, and the other that it should be as far as convenient from the magnet, the latter for its bearing on the conditions of balance. The location combining these two particulars to best advantage was found in the forward hold of the chaser. A serious drawback to this position was that entrance to the hold was

limited to a manhole 18 in. in diameter in the deck. However as none of the hatches on the vessel were large enough to accommodate a coil of the size required, it was realized that in any position below decks the coil would have to be wound in place.

The coil as finally wound was hexagonal in shape, this form being adopted for convenience in construction and assembly of the wooden form on which the coil was wound and permanently supported. Its dimensions, shown in Figure 10, were the largest possible in the available space, having in mind the importance that for the experiments it would be located with its plane athwartship, as well as at right angles to this position, and also that it should be kept a reasonable distance from the nearest steel bulkhead. In winding, the wooden form was mounted on an axis, and owing to the limited space, turned by hand. The wire reels were mounted on deck and the wire fed through the manhole. After completion of the winding the form was firmly braced into position, so that it became, as far as possible, an integral part of the framework of the vessel.

The coil had 5145 turns, average length of each turn 10.3 ft., corresponding to a circular diameter of 3.29. The volume of the winding, V_3, was 2.6 cu. ft.

The balancing coil, C_3', was located inside the radio room of the chaser, which was used as the centre of control and observation. Its location is shown at O. Several different balancing coils were used at various times. They were all of small size, less than 1 ft. in diameter and were mounted in wooden frames, permitting accurate adjustment about a diameter as axis. Sometimes two coils were used, one of them located near the magnet to take up the greater part of the electromotive force in the detecting coil. The final balance, both as regards

phase and magnitude of the net balancing e.m.f., was always accomplished from the observer's station, from which ready access could also be had to the rectifying commutator on the motor generator.

Practically all of the control equipment, including transformers, filters, condensers, switchboards, speed control and storage batteries, was located in the magazine. The amplifier and resistance for the final adjustment of the balance were located in the radio room in convenient reach of the observer at O.

All of the wiring was, as far as possible, carried in steel conduit or lead covered cable and all portions of the detecting circuit, transformers, speed control, etc., were placed in iron boxes for screening.

TOTAL WEIGHT.

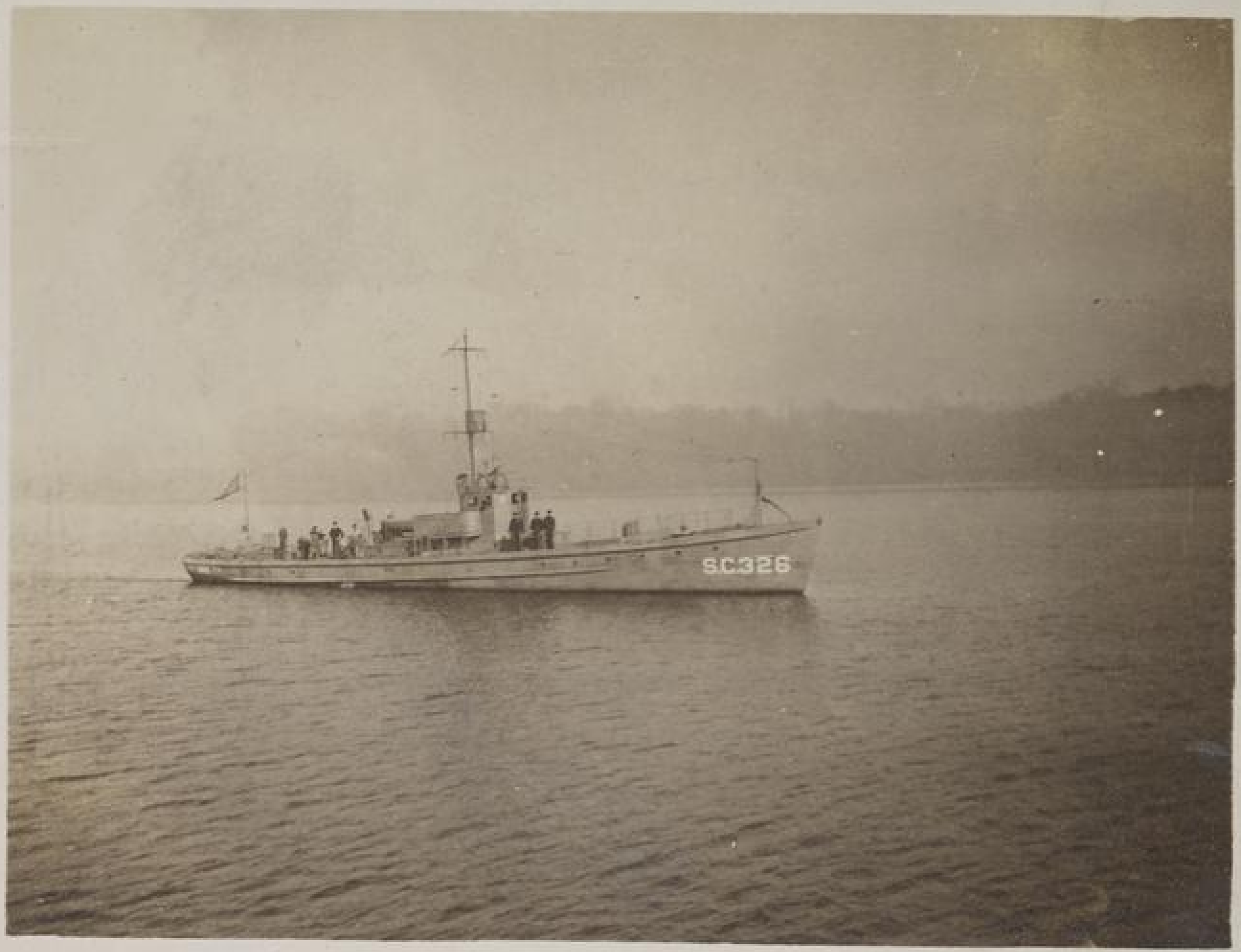
The approximate weights of the several portions of the equipment are as follows:

Magnet,	420 lbs.
Motor generator & Control,	2000
Detecting Coil,	1065
Amplifier,	150
Batteries and Auxiliaries,	500
Total,	4135 lbs.

As assembled, the only portion of the equipment appearing above decks was the magnet, whose housing was 10-1/2 ft. long and approximately one foot square in section. The space occupied below decks was limited to the magazine, the radio room, and a part of the forehold.

THE TESTS.

The detection tests were made on the steel converted yachts Wasp and Vega. The dimensions of the Wasp have already been given.



The S.C. 326.

The Vega.

The Wasp.

A Test.

The Vega was 179 ft. long, 20 ft. beam and approximately 15 ft. depth from keel to rail top. The thickness of her skin could not be ascertained, and it is assumed to be the same as that of the Wasp, 5/8 in.

The experiments embraced a great many preliminary tests on the conditions and stability of the balance in the detecting circuit. The congested condition, as regards the generator, magnet, transformer and speed control in close relation to each other in the magazine, introduced a number of new disturbances. In addition, the motion of the boat, both as regards its vibration and rolling, were also new types of disturbance. The phase of the magnetic field was found to vary in a most irregular way in different parts of the boat. Although the input transformer of the amplifier was enclosed in a triple nest of wrought iron screens, it was found to pick up very large inductive electromotive forces. In some positions of the magnet M_3 these stray electromotive forces were so large as to be comparable in magnitude with that in the detecting coil itself.

As a result of all the new disturbing factors, the use of the input transformer was abandoned in the later tests and the amplifier operated at either three or four stages. Under the best conditions available on the boat, therefore, the sensitivity of the detecting circuit was reduced to from one-half to one-tenth the value used in the shore tests, (see page 34), depending on the motion of the vessel due to the sea. It was considered that this degree of sensitivity was surprising and highly satisfactory for the conditions encountered. It was accomplished largely through the reduction of the electrical equipment to its simplest terms, by careful spring suspension of the amplifier, and rigid mounting of the detecting and balancing coils and of the magnet.

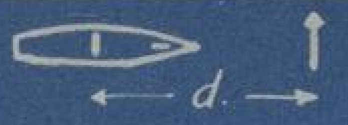
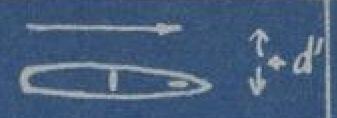
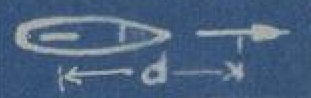
It should be stated at this point, however, that the degree of sensitivity, mentioned above, pertains to what would ordinarily be

described as good sea and weather conditions. Motion of the boat in high wind and heavy sea is immediately reflected in the detecting circuit. Sudden changes in engine speed and sharp changes of course also introduced corresponding upsets of the conditions of balance.

The detection tests were made sometimes with the vessel to be detected lying at the dock and sometimes in the open waters of Chesapeake Bay. Three kinds of tests were made; one approaching the submarine end on, that is, along the common axis of the two vessels; one passing the submarine, the two axes being parallel; and the third approaching the submarine as though to ram her amidships. The distances of detection were read with a range finder, or "stadimeter", the observer standing close to the magnet M_3. The distances were measured to the centre of the vessel to be detected.

A summary of the more important tests is given in Table 3. In this table the vessel on which tests were made is indicated in the second column by the initial letters of the Wasp and Vega respectively. In the third column, D gives the distance from the detecting coil to the magnet. The fourth, fifth and sixth columns indicate the relative position of magnet, coil, and vessels, and also the distances of detection. The seventh column gives, in some of the cases, the distance as computed from the shore tests on the Wasp. The eighth column gives the distance at which a reverse signal was obtained at a greater distance in a number of the tests. This signal was not permanent, in that with lessening distance to the submarine, the signal disappeared and the principal signal in opposite direction then followed. The remaining columns of the table give the particulars as to the detecting circuit.

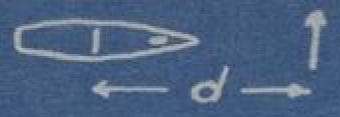
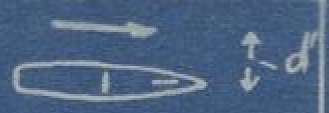
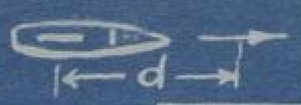
As a further indication of the general character of the experiments, the following extract from the daily record is given:

Date.	Vessel.							Reverse d. Signal.	Ampl'f'r Stges.	Galvanometer -Ohms.		Balance.	Signal Div'ns.
		D.	d.	d.	d'.	d.	Dist. Calc.			Sh.	Ser.		
1918.									W.E.	Weston.			
11-5	V.	33	159		120				2				
11-6	V.	25				240					1000	Bad.	
						225		360	2		1000		
						195					1000		
						108					1000		
						147		330			1000		
						129		270			1000		
						150					1000		
11-7	V	25				100			2			good	
						150							
11-16	W	25		131				350	2			good	
										S + H.		good	
11-21	V	80				200			4	10	1000	0 ± 2 dn	15
						185							15
						185							15
						200	240		3	10	50	good	10
						200	240						20
					90				4	10	1000		25
11-27	W	47	125				178		4	10			
				140	69								
				160									
11-29	W	25	115	165	90				4	10	1000		
			130										
12-5	W	25	135				120		4	10	500	Very good ± 10	35
			127				120						35
			150				120						35
			196				120						40

Distances d + d' in feet.

~ Table 3. Summary of Tests Afloat. ~

Page I.

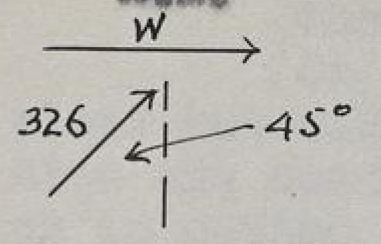
Date	Vessel.							Reverse Signal	Ampl'f'r St'ges	Galvanometer Ohms		Balance	Signal Div'ns
		D.	d.	d.	d'.	d.	Dist. calc.	d.		Sh.	Ser.		
12-5 con'd.	W			120						G+H.		±5	10
				120									15
			85										
			92										
			83										
					90								
		50		144					4	10	100		
		50		210	105			210					
12-9	W	50	96						4	10			30
		50	112										
12-10	W	50		195	72			195	4	10		good	15
				375	85			375					
				330	100			330					
12-20	W	50			75				4-	10	200	good	35
				100	72							±5	35
				120	72								35
			100				146	285					
			70				146	180					
			180				146	225					
									G.E.				
12-21	W	50		150	120					10	100		20
				195	75				4				25
				135									
		50	127				156						
			157				156						
			221				156						
			142				156						

Distances d+d' in feet.

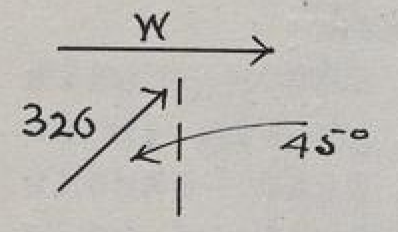
~ Table 3. Summary of Tests Afloat.

Page II.

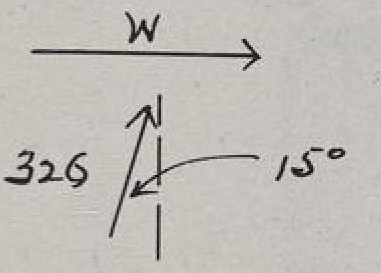
Dec. 5, 1918, A.M. Restored 3 and 4 stage balances; good sensitivity.
Detection tests on Wasp (at dock), strong north wind,
4 stages, 2, 3, 4, 5, no transformer, no filter,
galvanometer, 10 ohm shunt. Observer standing at M.



Signal off scale
at stadimeter reading 900
d = 135 ft.; zero ± 15 divisions.

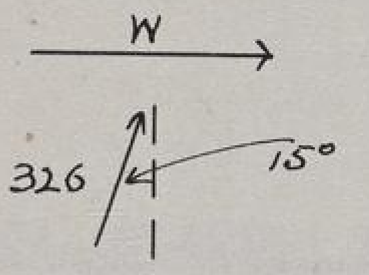


4 stages, galv., 10 ohm shunt, 500 ohm series, zero ± 10 div.
Signal off scale
at stadimeter reading 850
d = 127 ft.



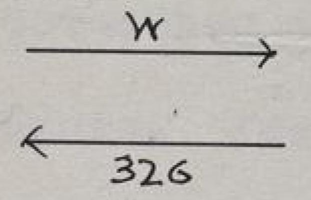
Signal 35 divisions (off scale) conditions very good.
at stadimeter 1000
d = 150 ft.

Needle returned to zero at greater distance, but masked by Reina Mercedes. The increase of signal with decreasing distance is much slower than indicated by inverse sixth power.

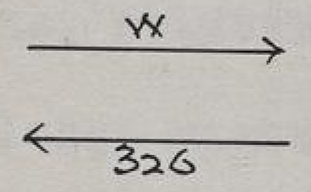


Signal 40 to 50 divisions, Return to zero after
at stadimeter 1300 leaving neighborhood
d = 196 ft. of Reina Mercedes.

Test of scale reading of zero back and forth across strong wind, difference: 15 or 20 div., in same direction as above signal.

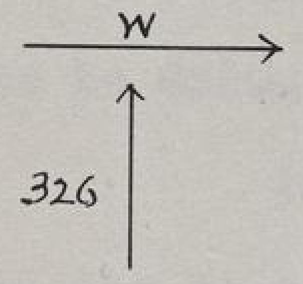


4 stages, 2, 3, 4, 5, galv., 10 ohm shunt,
500 ohm series, zero ± 5 div.,
Signal 10 to 15 divs. and doubtful,
at stadimeter 800 Reina Mercedes gave opposite signal.
d = 120 ft.

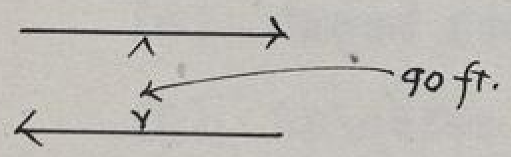


Signal +10 to +15 divisions
at stadimeter 800
d = 120 ft. Reina Mercedes gives reversal.

Dec. 5, 1918, P.M. Moved magnet to bridge back of pilot house, to repeat tests of 11/26. Wasp, at dock.

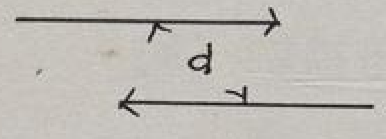


4 stages, 2, 3, 4, 5, galv., 10 ohm shunt, 100 ohm series.
3 runs, signals off scale.
up out
stadimeter 570=85 ft.
610=92 ft. 1000=150 ft.
550=83 ft. 650= 98 ft.



600=90 ft., strong + signal off scale.

970=144 ft., 10 to 15 divisions negative followed by positive signal when abreast.



1400=210 ft., 10 to 15 divisions negative followed by strong off scale positive signal, when abreast at 700=105 ft.

Conditions of the above tests very good.

On a straight course the zero was constant to ± 5; it was clear however that when the course is changing the zero is upset. Also the condition of the balance is always worse at higher speed, or in motion due to waves, - the zero reading often follows the roll of the boat.

The morning tests were especially significant - there was a strong north wind down the Severn, and the →↑ tests were across the wind, giving a slight roll - the influence on the zero was quite obvious. Also the zero was shifted 20 divisions by going across the wind in opposite directions.

Conclusions: We have available considerably more sensitivity than can be used, owing to vibration and motion of the boat. Distances above 200 ft. can be reached in quiet water and at slow speeds.

The signals are of opposite sign, depending on the relative position of Wasp and S. C. 326, but the law followed has not been studied.

Tests have shown the disturbing influence on an otherwise stable zero reading (to ± 5 at 4 stages, 10 ohm shunt), of the direction of the wind, the roll of the boat, a change of speed, high speed, a change of course.

CALCULATION OF DISTANCES TO BE EXPECTED.

In planning the equipment for the Submarine Chaser #326, the detection tests on the Wasp with the shore equipment were used as a basis. For example, the tests of Aug. 14, 1918, show an average distance of detection with the Wasp of 390 ft. for an end-on test, that is, relative arrangement B. In these tests the excitation of the large magnet was 19.6 K.V.A. and the value of D was 70 ft. These, and the other corresponding constants pertaining to the Wasp tests, were substituted in Formula (11) and the corresponding value of K was found to be 4590.

In passing to the equipment of S. C. 326, a number of changes in the equipment were made, notably in the following particulars:

(a) Cross section and magnetic flux density of magnet.

(b) Relative position of magnet and vessel.

(c) Change in amplifier and galvanometer sensitivity.

(d) Effective length of the submarine as affected by the distance at which detection was first noted.

In computing distances to be detected, corrections must be made for alterations in each of these particulars, and the general method of applying these corrections has been described in connection with the tests on shore, beginning on page 24.

The expected distances of detection have been worked out for a few cases in which the relative positions of the two vessels permitted it. For example, in the tests of November 21st, the observed distances of detection were in the neighborhood of 200 ft. For the computed distance, the constant 4590, as derived from the Wasp tests, was used in Formula (11). The magnetic flux density for M_3 was three times that in M_2, introducing therefore a factor 3 inside the bracket of Formula (11). In order to maintain satisfactory balance conditions, 50 ohms was inserted in series with the galvanometer and its 10 ohm shunt. The change in sensitivity on this account introduces a factor of .615 into the bracket of Formula (11). Obviously, the physical constants for the Vega and for detecting coil C_3 must also be introduced into Formula (11), giving the resulting computed distance of 240 ft., as shown in the table. In this end on position, no correction is introduced on account of a shortened effective length of magnet.

The tests of November 27, December 5, 20, and 21 pertain to relative arrangement A for magnet and submarine. Corrections similar to those described above are made in each of these cases. In addition a further factor must be introduced into the bracket of Formula (11), by reason of the shortened effective length of the vessel to be detected. For example, as shown in Appendix F, at distances of detection of 125 ft. and 200 ft. the net effective lengths l_3 of the submarine are .51 and .72, respectively, of the actual length. In making the corrections the factors for the effective lengths are taken for the observed distances of detection from the curve of Figure 22, Appendix F.

It will be observed that there is a very fair agreement between the distances as observed and as computed. While the observations are below the computed values for the tests Nov. 21, 27 and Dec. 20, higher distances of detection are found in the remaining cases.

Attention is directed to the reverse signal recorded in the ninth column of Table 3. These signals are invariably at greater distances than those computed. They were always of brief duration and, on closer approach to the submarine, quickly changed to a signal of opposite sign, the latter signal being much more pronounced in its character. This latter signal is the one which has been used throughout. The initial reverse signal was, for a long time, attributed to some extraneous disturbance, but its frequent reappearance finally led to the conclusion that it was really a genuine signal of detection. No obvious explanation of this signal offers itself, unless possibly that in some positions the direction of approach of the vessel detected passes through some irregular distortion of the field of the magnet. That there were numerous occasions in which this signal was not observed, there is no doubt; consequently, attention is called to it only as an interesting observation which cannot be used as a basis of conclusion.

GENERAL CONCLUSIONS.

The principal conclusions from the detection tests are as follows:

(1) Detection tests in the laboratory with submarine models 10 ft. long are in agreement with underlying theory and may be used as a basis for the design of larger equipment.

(2) Detection tests on steel hulls from shore equipment and from equipment installed on a wooden submarine chaser 110 ft. long are in good agreement with results predicted from a formula developed in the laboratory tests.

(3) By sufficient increase in the size of the equipment it is possible, in quiet water, to detect a steel vessel 200 ft. long at a distance of 500 ft. The weight of equipment required would be about 8000 lbs.

(4) Distances of detection in the neighborhood of 200 ft. were obtained in quiet water with equipment weighing 4500 lbs. installed on a wooden submarine chaser 110 ft. long.

(5) The reliability of the system of detection is immediately impaired by motion of the vessel, due to her engines, heavy sea, and changes of course, or speed.

(6) The results mentioned involve the use of amplifier tubes for enlarging the signal. Without the amplifier the distances of detection are very short, even when a large magnet or large detecting coil and an extremely sensitive detecting instrument are used.

(7) With amplifier, detecting coil and detecting instrument higher sensitivities may be reached than can be

used in the detection tests. Disturbances in the detecting system fix the limit for increasing sensitivity. These disturbances are amplified and appear in the detecting instrument as larger than the signal sought.

(8) The problem of increasing the distance of detection is that of eliminating disturbances in the detecting circuit. The most common types of disturbance, in the order of their importance, are (a) relative motion between magnet and detecting coil due to vibration and strain of the vessel, (b) small variations of frequency of the alternator, (c) harmonic components of the alternating signal in the detecting coil, (d) variable inductive disturbances, (e) vibration or motion of the amplifier and other parts of the equipment.

(9) The greatest promise of improvement over the results reported lies in the elimination of disturbances (a) and (c). A rigid connection between the magnet and detecting coil, so that they form one structure, would probably constitute a great improvement. The use of a "band filter" in the amplifier input circuit, passing frequencies in the neighborhood of 30 cycles only, should also introduce a marked improvement. There appears no possibility of securing greater constancy of speed than that reached in the experiments. The utmost possible precautions, in connection with the other disturbances mentioned, should always be used.

(10) Other interesting conclusions at various stages of the work will be found in the several appendices.

APPENDIX A.

MAGNETS AND COILS.

MAGNET M_1.

This magnet, used in the laboratory tests at the Johns Hopkins University, has been described on page 14, and the general method of applying the exciting winding is shown in Figure 7. The purpose of the multiple winding is to increase the effective length of the magnet and, as far as possible, to prevent variations in this effective length with variation of frequency and voltage.

The distribution of flux in this magnet is indicated approximately in Table 4, in which the first column gives the distance of an exploring coil from one end of the core, and the second column the corresponding voltage induced in this coil. The figures show that the flux is fairly uniform over the whole length of the core, falling off rapidly, however, for positions outside the ends of the magnetising winding.

Table 4.

Distribution of Magnetic Flux
in Multiple Wound Magnet M_1.

Distance from one end - inches	Volts in Exploring Coil.
1	3.22
6	5.05
11.2	4.80
15.7	4.90
22	4.84
27.7	4.84
33.5	4.84
39.2	4.70
45.2	4.75
51.2	4.71
58.2	4.70
61.7	4.82
65.7	4.95
71	2.95

Additional data on Magnet M_1 are given in Table 5, page 53.

Magnet M_1.

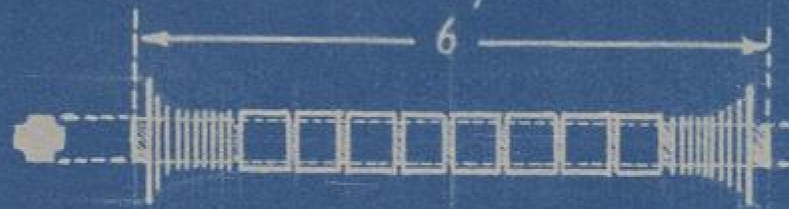


Fig. 7.

~28 coils, 52 turns each, connected in parallel.
Outer coils ~ 4 #6 B.&S. square wires in parallel.
Central coils, #10 B.&S.
Total Flux at 22.6 volts, 4.52 KVA, 30 cycles, = 342,500 c.g.s. lines. ~

Magnet M_3.

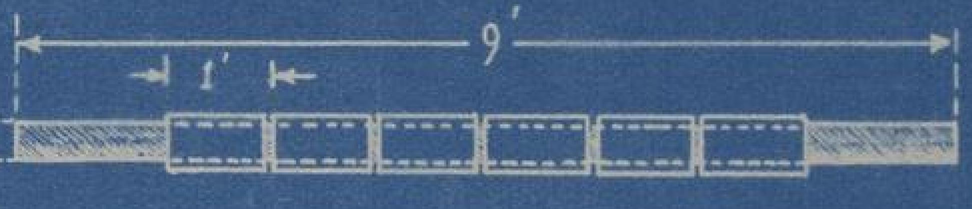


Fig 8.

~ 6 coils, 104 turns #10 B.&S. wire, connected in parallel.

Total Flux at 70 volts, 3.15 KVA, 30 cycles, = 510,000 c.g.s. lines. ~

Magnet M_2.

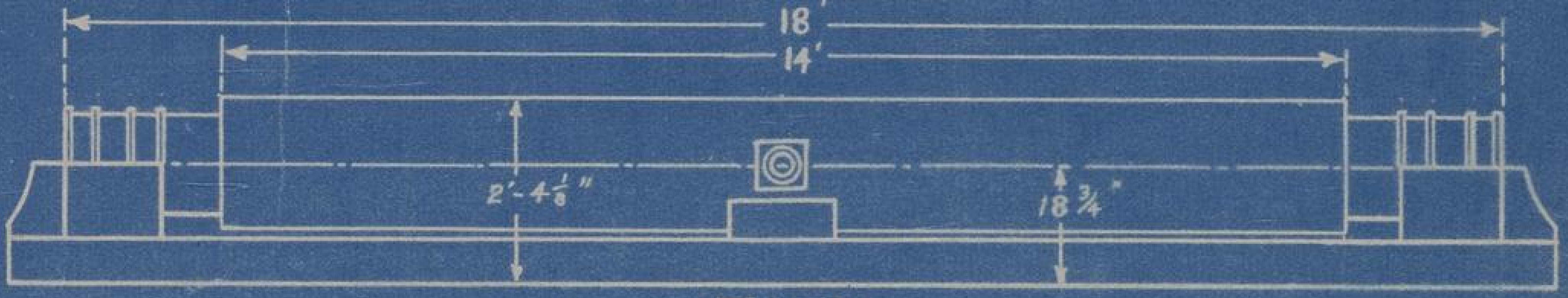
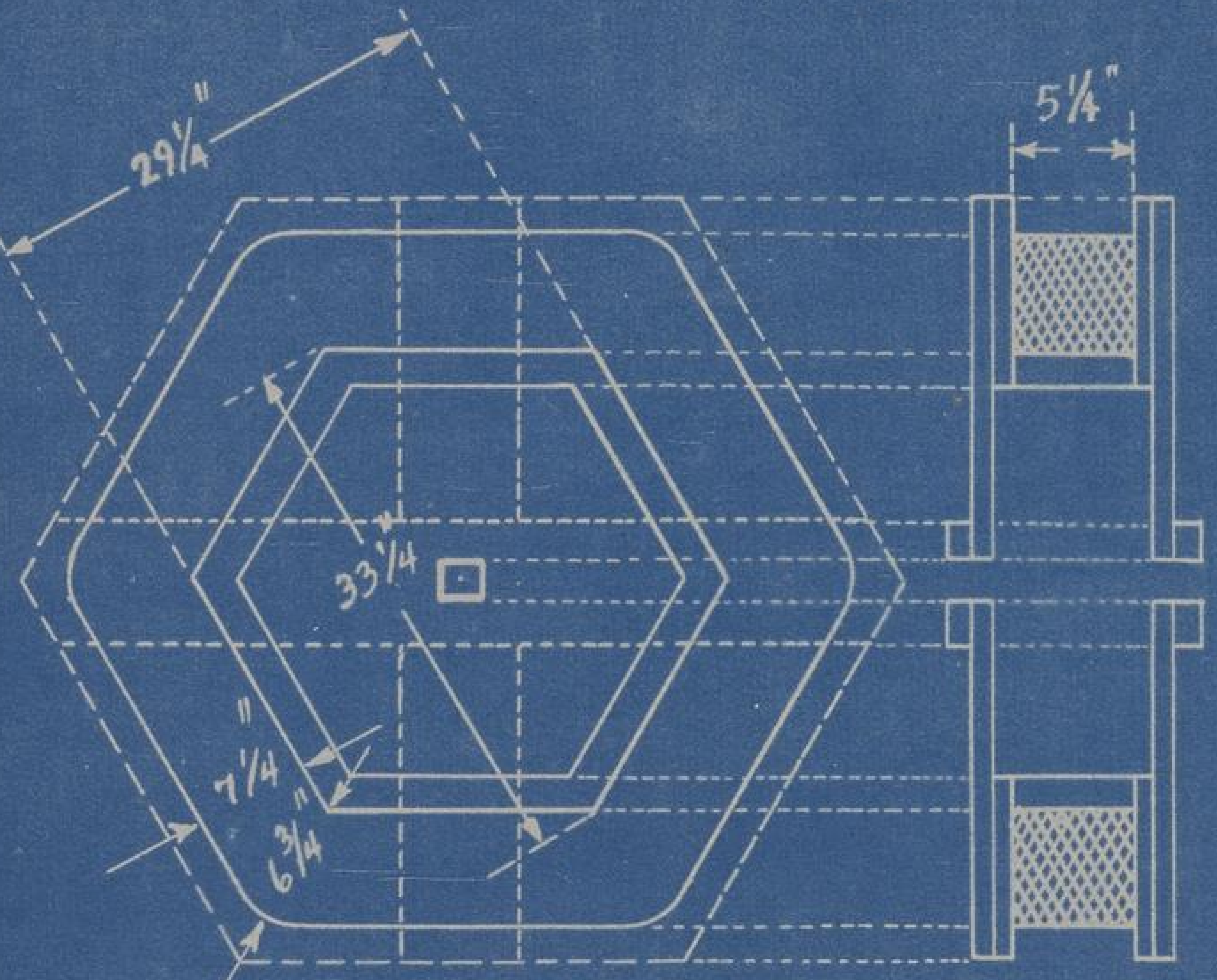


Fig 9.

~ 266 coils. ~ Total Flux at 115 volts, 25 KVA, 30 cycles, 2,160,000 c.g.s. lines. ~



Coil C_3. ~

5145 turns of #10 B&S. D.C.C. wire, in 87 layers.

Fig. 10.

MAGNET M_2.

This magnet was designed by the Westinghouse Electric & Mfg. Co., to give the largest possible magnetic moment with an excitation of 26 K.V.A. at 30 cycles. It has a distributed winding with multiple connection of the same general character as that of magnet M_1, the number of coils, however, 266, being much greater. Data as to the number of turns, size wire and dimensions of the respective coils have not been given by the manufacturer. The whole winding is imbedded in weather proof compound with protective covering.

The pole pieces of the core are relatively longer than in the earlier magnet M_1, thus reducing the amount of copper necessary in the end coils. The laminated core is built up around a wooden cylinder and the cross section of iron is not given. The outside diameter of the combined wooden and iron core, which is circular in cross section, is about 1 ft. The completed magnet is mounted on saddles in a strong and rigid wooden frame.

The electric and magnetic constants are given in Table 5.

MAGNET M_3.

This magnet differs from magnet M_1 principally in its relatively longer pole pieces, the object being to still further reduce the excitation required. As a result, this magnet required a smaller K.V.A. consumption and had a greater magnetic flux and magnetic moment than M_1. Its length was about as great as could be comfortably handled in various positions on the deck of S. C. #326.

Table 5.

MAGNET DATA.

		M_1	M_2	M_3
Length of Core		6 ft.	18 ft.	9 ft.
Length of Winding		5 ft. 9 in.	14 ft.	6 ft.
Number of Coils		28	266	6
Turns per Coil		52		104
Effective Length of M		5 ft. 10.5 in.	16 ft.	7.5 ft.
Cross Section, sq. in.		8.81		7.7
Equivalent Radius		1.65 in.		1.57 in.
Rated Excitation	Volts	22.6	115	70
	Amperes	200	226	45
	K.V.A.	4.52	26.0	3.15
Power Factor		.2	.091	.13
Total Flux		342,500	2,160,000	510,000
Moment C.G.S. Units		$6.13x10^7$	$105.2x10^7$	$11.7x10^7$
Weight		386 lbs.	4000 lbs.	420 lbs.

DETECTING AND BALANCING COILS.

The data pertaining to the three detecting coils used in the three main divisions of the work are assembled in Table 6. The largest coil, G_2, was built by the Westinghouse Electric & Mfg. Co. and was rigidly mounted in a wooden framework. The winding was thoroughly water proof and enclosed in a protective wooden covering. This coil was designed for out of door service.

The detecting coil, G_3, was located in the small forehold of the chaser. This coil had to be wound by hand, its wooden form having been constructed outside and then assembled in place. Owing to the limited space, the winding of this coil was a tedious matter. However, when completed the substantial wooden form and its proximity to the

timbers forming the frame of the ship offered a ready means for thoroughly bracing it in position. It contained approximately 900 lbs. of No. 13 double cotton covered magnet wire and was suitably protected against moisture and damage.

A variety of balancing coils were used in different stages of the work. In the experiments in the laboratory and on S.C.#326 three coils were used, all having the same dimensions as those of detecting coil C_1, but having 2000, 1000 and 306 turns, respectively. The balancing coil C_2' was of special weather proof construction, as described for detecting coil C_2. It was three feet in diameter and had 530 turns. It was provided with a worm gear for rotation about a diameter as a vertical axis and also had a gear for a short rectilinear translation. Both of these features were for the purpose of accurate adjustment in balancing. All metal parts were of brass and the entire coil with its adjustment was mounted in a substantial wooden framework.

Table 6.

DETECTING COIL DATA.

Coil		C_1	C_2	C_3
Diameter	Outside	9.5 in.	85.5 in.	[1]31.25 in.
	Inside	5.75 in.	82.5 in.	[1]47.7in.
	Average	7.625 in. .635 ft.	7.0 ft.	[1] 3.29 ft.
Axial Thickness		1.25 in.	3 in.	5.25 in.
Depth of Winding		1.87 in.	2.93 in.	7 in.
Volume in cu. ft.		.0325	1.344	2.63
No. of Turns		2000	1308	5145
Resistance		70 ohms	60.07 ohms	99 ohms
Inductance		1 henry	8.22 henrys	[2]53 henrys
Weight		9 lbs.	1500 lbs.	1100 lbs.

1 Estimated from dimensions of hexagonal coil.

2 Calculated by means of Doggett's formula.

APPENDIX B.

DETECTING AND MEASURING INSTRUMENTS.

In the early stages of the work, when sensitivity was a desideratum, suspension type D'Arsonval galvanometers were used as detecting instruments. It was realized, however, that such an instrument could not be used on shipboard, and as soon as the amplifying equipment was available, the instruments were abandoned. Descriptions of the two which were used are given in Table 7. At one time the commutator was suspected as a possible seat of troubles in balancing the detecting circuit. A unipivot type electro-dynamometer was therefore tried for direct measurement of the signal in the detecting circuit as an alternating current. Experiments with this instrument, however, gave indication that the disturbances in question were due to other causes. Furthermore, the sensitivity of the electro-dynamometer was lower than that of the most suitable D'Arsonval instrument available and offered certain difficulties in the process of balancing the detecting circuit, notably the steps necessary for eliminating the residual or out-of-phase component. The sensitivity given in Table 7 for this instrument pertains to a value of 2 amperes, 30 cycle, alternating current in the stationary coil, the highest rated value for continuous service.

A further effort in the direction of increased sensitivity without the commutator was made in a series of experiments, using an Einthoven string galvanometer. The aim here was to reduce, as far as possible, the number of stages of amplification necessary. Two strings were furnished with this instrument, one of silver and the other of silver quartz. The extreme value of 3.5 times 10^{-16} watts direct current per division of sensitivity was claimed for the instrument using the quartz string.

As compared with the commutator and continuous current galvanometer, the Einthoven string galvanometer is subject to the

following limitations. With the former combination, in the process of balancing, any out-of-phase residual which may be left in the detecting circuit is chopped up by the commutator and appears, if at all, only as a slight vibration of the needle in its zero position. The same statement may be made with reference to any harmonic disturbances which may be present. With the string galvanometer, both the residual and the harmonic will produce a vibration of the string in exact proportion to their intensities. In the experiments with the string galvanometer, these residuals were always found to be present, and since only small intensities are necessary to produce deflections equal to that pertaining to a strong signal, this sets a definite limit to the sensitivity that may be used with the string galvanometer. A number of rough detection experiments were made, but it was found that the limits mentioned resulted in very much lower distances of detection than found in the case of amplifier, commutator, and continuous current galvanometer. There remains the possibility of filtering out the harmonics using one or two stages of amplification, and so making use of the extreme sensitivity of this type of instrument. However, it appears probable that the process of balancing would have to be accomplished with the use of other equipment, and there is always the question of the behavior of such an instrument on shipboard.

Two instruments of special type were constructed by the Weston Electrical Instrument Co. They are described as Weston No. 2 and No. 3 in Table 7. Instrument No. 2 was found to be not suitable on account of the delicacy of its suspension. Instrument No. 3 was designed especially to dampen out, as far as possible, irregular motions of the galvanometer needle in its position of balance. This instrument, therefore, was heavily damped and its moving part had a relatively high moment of inertia. The weight necessary, and the consequent force per

unit area on the bearings, puts a low limit to the moment of inertia of a sensitive pivot coil instrument; consequently, in this instrument an attempt was made to improve the balance conditions by the use of high and variable damping. This was accomplished in the 2-pivot special Weston galvanometer No. 3, by electro-magnetic excitation of its field. In addition to the constants given in Table 7, the instrument had the following characteristics:

Moment of inertia of coil,	2 gr. cm.^{2}
Undamped period,	1.65 seconds
Interval shunted with 80,000 ohms,	7 seconds
Interval when connected to last stage of amplification and with field fully excited,	80 seconds.

By sacrificing some sensitivity, the extremely long interval mentioned, when connected for testing, could be reduced by reducing the field excitation. For the same sensitivity of detection the instrument could be used with one stage of amplification less than that pertaining to the instrument which was used for practically all the other tests. It showed no other decided advantage over the latter instrument which is described below. The possibility of using one less stage of amplification offers some advantage and the instrument was used in a large number of tests. However, it was not as rugged as the instrument next to be described and which supplanted the Weston instrument in all of the later tests on shipboard.

BEST FORM OF DETECTING INSTRUMENT.

The most satisfactory detecting instrument of all was a Siemens & Halske, double pivot, D'Arsonval type, portable needle galvanometer. This instrument had a central zero and a complete scale of 25 one-millimeter divisions on each side. Its resistance was 100 ohms and its sensitivity 10^{-6} amperes per division. Its critical damping

resistance was 90 ohms. This galvanometer withstood all the hard usage of over a year of experiment, and was continuously subjected to various forms of accidental unbalancing, resulting in excess currents, and to the many extreme manifestations of "wiggles" and "shakes" of the needle arising from unforeseen unbalanced resultants, harmonics and extraneous disturbances amplified several hundred times. It had a clear and open scale for direct reading and was in every way superior to all other instruments tried, from the standpoint of convenience and rugged construction. At the end of the experiments its sensitivity was found by test to be unimpaired. Efforts were made to find an instrument of the same general type which would have a higher sensitivity, but when increased sensitivity was found it developed that it was at the sacrifice of either length of scale or substantial construction.

Table 7.

CONSTANTS OF DETECTING INSTRUMENTS.

Instrument	Type	Resistance	Sensitivity	Critical damping resist.	Watts per division deflection
S & H	Double Pivot D'Arsonval	100 ohms	10^{-6} amp./div.	90 ohms	10^{-10}
L & N	Wall Type Suspended Coil	101 "	$1.2x10^{-8}$ "	300 "	$1.44x10^{-14}$
L & N Ballistic	Wall Type Suspended Coil	1180 "	$8x10^{-10}$ "	3500 "	$7.5x10^{-16}$
Electrodynamometer	Paul Unipivot Central Zero	60 "	$1.4x10^{-6}$ "		$8.4x10^{-11}$
Einthoven String galvanometer	Silver string Silvered quartz String	8.8 " 2350 "			$3.29x10^{-14}$ D.C. $3.5x10^{-16}$ D.C.
Weston #2	Suspended Coil Needle Galvanometer	500 "	$8x10^{-8}$ "	800 "	$3.2x10^{-12}$
Weston #3	Double Pivot Electromagnetic	1570 "	$5.7x10^{-8}$ "	80000 "	$5.1x10^{-12}$

TELEPHONE RECEIVER AS DETECTOR.

A number of tests were made with telephone receivers in place of the commutator and galvanometer. Obviously 30 cycles is too low a frequency for audibility. Consequently in order to use the telephone receiver it is necessary to interrupt at sufficiently high frequency the current constituting the signal from the detecting circuit. This was accomplished by placing in series with the telephone instrument at the output end of the amplifier a "chopper", the speed of which could be adjusted for any desired pitch tone for the telephone. Three different forms of chopper were tried, (a) simple interrupter, (b) condenser chopper with sliding contacts and (c) condenser chopper without sliding contacts. All were relatively small machines driven by direct current motors of variable speed. No further description of these choppers need be given here, as no promising results were obtained from any of them. The invariable trouble was that even at low sensitivity, as regards amplifier and detecting instrument, it was found practically impossible to balance for zero noise in the receiver. Moreover, it was found that under best conditions as to quietness,the electromotive force in the detecting circuit necessary to give a signal was considerably in excess of that required to give a full scale deflection on any one of the galvanometers as detector.

No special study was made of the characteristics of the telephone receiver itself, but four or five different receivers collected from the laboratory telephone and radio equipments were tried. The fact that it was found impossible to eliminate sound in the balanced condition, even with low sensitivity equipment led to the conclusion that this was not the most promising direction in which to look for a higher sensitivity. Moreover, the telephone has in common with the Einthoven galvanometer the disadvantage that it needs an auxiliary equipment for balancing, nor does it give a quantitative indication.

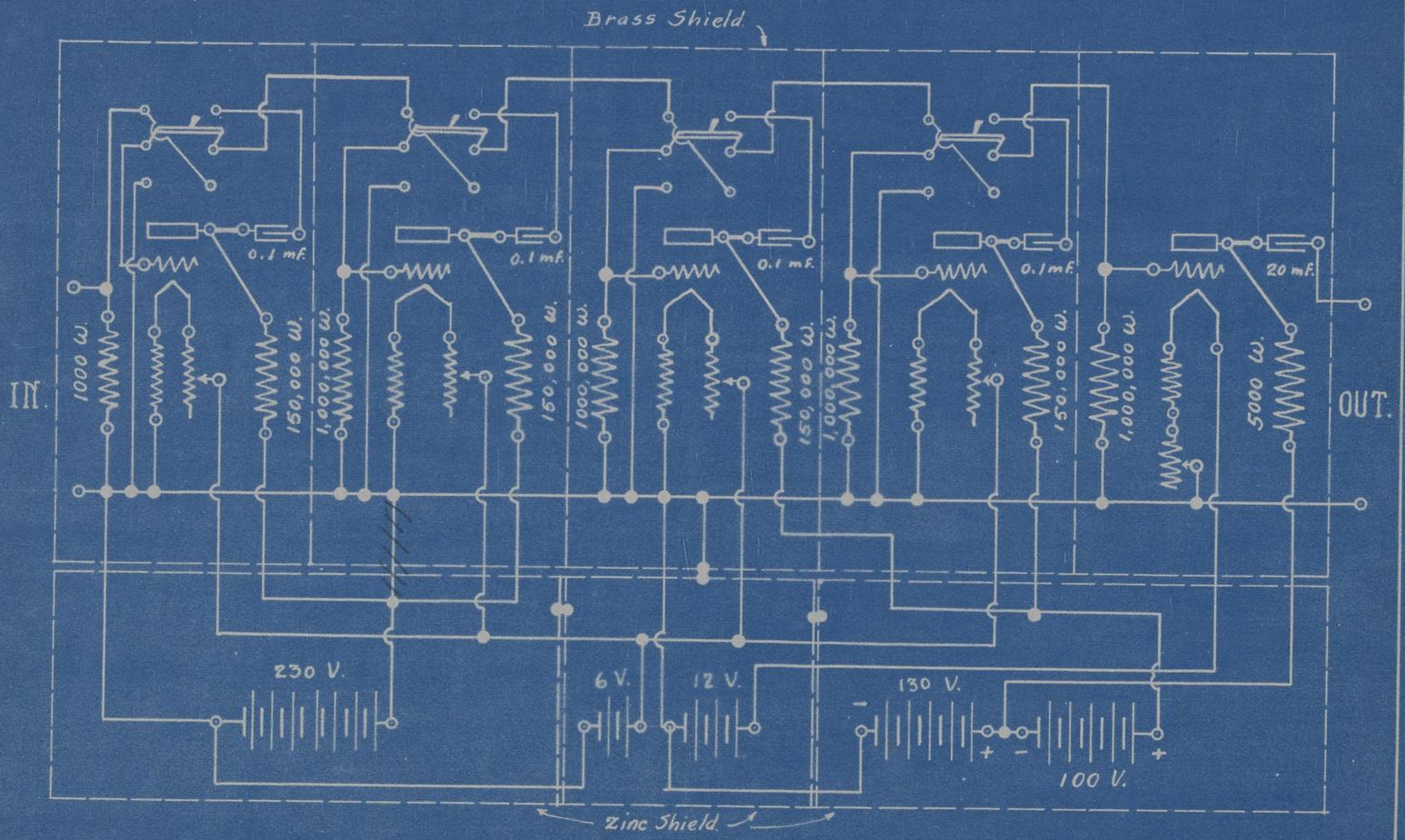
APPENDIX C.

AMPLIFIERS.

On page 27 it was shown that when using a detecting instrument of quite high sensitivity it is necessary to go to very large sizes of the magnet and detecting coil, in order to reach even moderate distances of detection, if no other means are used for increasing the sensitivity.

In all of the subsequent experiments amplifying tubes were used for increasing the sensitivity. The general principle of the operation of these tubes is now well known. The tube has a hot cathode, consisting of a filament excited by continuous current, a plate anode and an intermediate electrode, known as the grid. A continuous voltage as applied between the cathode and anode, resistance being connected in series. The hot cathode emits electrons, thus permitting a constant flow of current between anode and cathode. The amount of electronic emission of the cathode is extremely sensitive to slight variations in the potential gradient in its neighborhood. When used as an amplifier these potential variations are brought in by means of the grid. The resulting changes in the current passing through the tube cause corresponding changes in the voltage drop over the resistance in series with the plate, and consequently very small variations in the potential of the grid are transformed into much larger variations in the potential across the resistance.

The amplifier that was used for the greater part of the detection experiments was constructed specially for this work by the Western Electric Co., and had five stages of amplification, the successive stages being coupled by means of resistance. Figure 12 gives a diagram of all the connections, including the filament and plate batteries. Stages 1, 2, 3 and 4 were of high impedance, the plate to filament



5-Stage Amplifier. Fig. 12.

resistance being 150,000 ohms. The fifth stage was of lower impedance, the plate to filament resistance being only 5,000 ohms. The amplifier was designed for an output impedance of 500 ohms. The most satisfactory detecting instrument developed by subsequent experiments had a resistance of about 100 ohms and a critical damping resistance of 90 ohms. Consequently, an output transformer was used with the amplifier to adapt its output characteristics to those of the instrument. This transformer had a primary impedance of 5,000 ohms at 30 cycles and a secondary impedance of 50 ohms. The primary of the transformer was substituted for the 5,000 ohm resistance in series with the plate battery shown in the fifth stage.

The voltage amplification, as measured by the manufacturer, with an output resistance of 530 ohms and always using the low impedance stage for the output was as follows:

3 stages	110 times
4 "	1,300 "
5 "	18,000 "

In the experiments on land an input transformer was also often used with the amplifier. In voltage amplification this transformer was somewhat better than one additional stage and used with the transformer, the amplification as given by the manufacturers was:

3 stages	2,600 times
4 "	93,000 "
5 "	1,270,000 "

The impedance of the primary of the input transformer at 30 cycles was in the neighborhood of 70 ohms. Its secondary impedance was very high so that when the transformer was used, the 1000 ohm resistance across the input of the amplifier was removed.

The input transformer was placed in a triple nest of wrought iron boxes, each 3/16 in. thick. Nevertheless, the transformer picked up enough inductive disturbance from the 30 cycle and other circuits to give serious trouble. On land this inductive electromotive force was reduced as much as possible by orienting the transformer until it had a small value. Any small residual from the 30 cycle circuit could be balanced out. The presence of this disturbance, however, often gave serious difficulty in determining the proper commutator setting and in adjusting the capacity to be used in the detecting circuit. On board ship, where the limitations of space prevented a proper choice of the location of this transformer, it was finally abandoned. The loss of amplification was made up by an additional stage of the amplifier, the transformer and three stages having been used in the land tests and four stages of amplification without transformer being used on board ship.

PRECAUTIONS IN USE OF AMPLIFIER.

Having in mind the figures of amplification given above, it will be readily seen how necessary it is to eliminate all types of disturbance in the detecting and amplifier circuits. In using four, or even three stages, very minute disturbances are amplified to magnitudes greater than that of the detection signal due to the submarine.

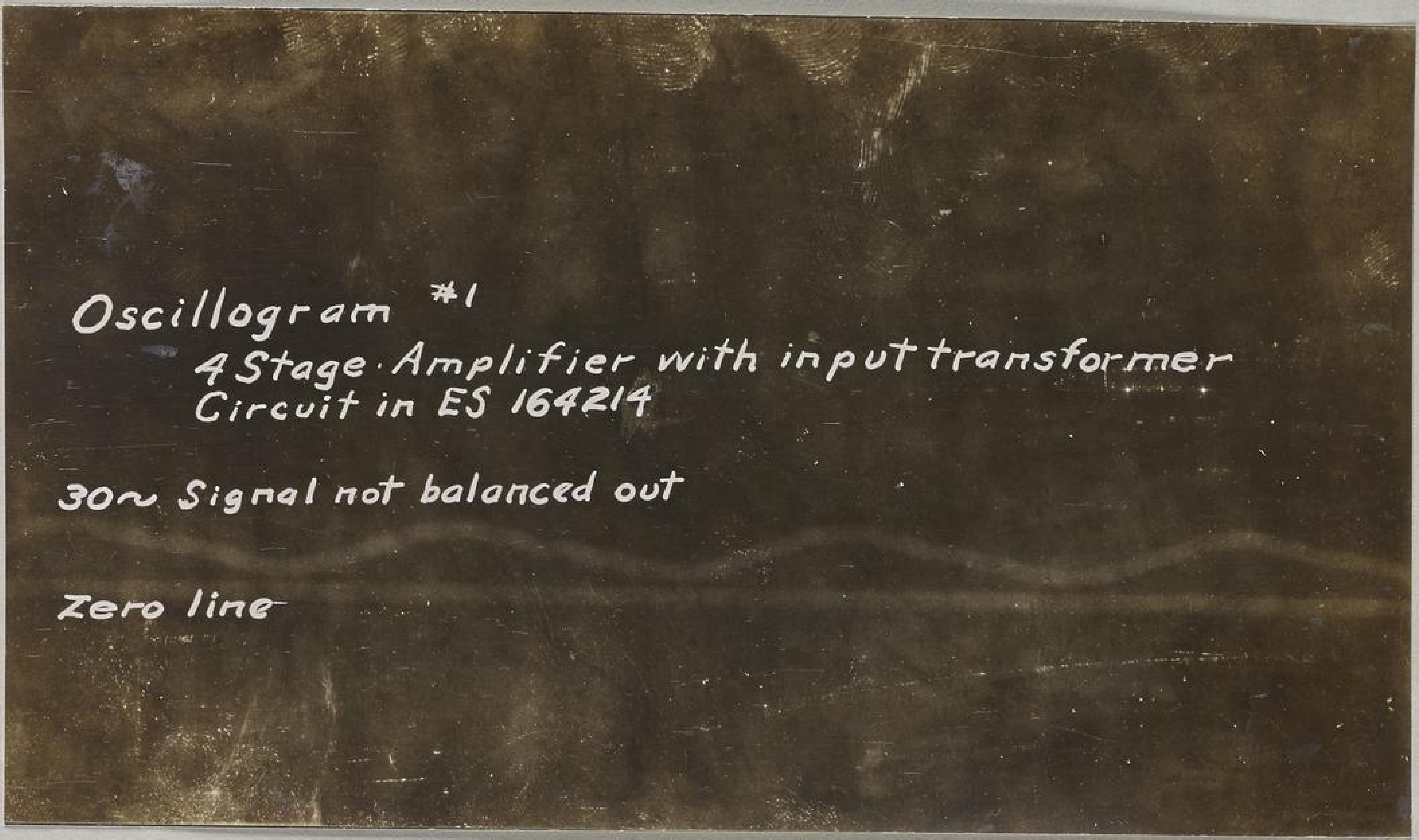
Perhaps the commonest types of disturbance are those due to (a) poor connections and contacts in battery, amplifier and detecting circuits; (b) poor electro-static and electro-magnetic shielding. The amplifier itself and all leads should, as far as possible, be enclosed in grounded shields; (c) duplication of ground connections. All shields, conduits and cases should be connected to the same ground; (d) mechanical vibration of the amplifier. Very slight motions of the filament with reference to the grid cause variations in the tube

impedance with resulting variations in output voltage. Careful spring suspension of the amplifier is therefore advisable.

Any of the foregoing types of disturbance which may be present will appear with no input in the detecting circuit, consequently with care all should be reduced to small values. On land it was found that they could be eliminated to such a degree that four and sometimes five stages could be used, resulting in a quiet galvanometer needle. There are, however, two other types of disturbance which are generally present in practice. They are (1) electromotive forces induced in the detecting circuit by neighboring circuits, (2) harmonic electromotive forces which are not balanced out.

When the inductive disturbances are of a frequency somewhere near 30 cycles, their presence is indicated by a slow oscillation of the galvanometer needle from one side to the other, the period depending upon the frequency of the disturbance. If the frequency of the disturbance is quite high, it may not cause a deflection of the needle, but result simply in a violent vibration. The oscillogram of Figure 11, taken at the output of the amplifier, shows a disturbance which was finally traced to a high commutator bar in a generator supplying some of the circuits of the neighboring building.

When the frequency of the disturbance, whether due to harmonics or to neighboring circuits, is greater than 40 cycles, it can be eliminated by means of "filters" or "pilot conductors" of the general character of those shown in Figures 13, 14, 15 and 16. Figure 13 shows a filter for use at the output end of the amplifier; Figure 14 one designed for 70 ohm terminal conditions, that is, for use between the detecting coils and the primary of the input transformer. The pilot conductors were designed to go between successive stages of the amplifier.


Oscillogram #1
4 Stage Amplifier with input transformer
Circuit in ES 164214
30~ Signal not balanced out
Zero line

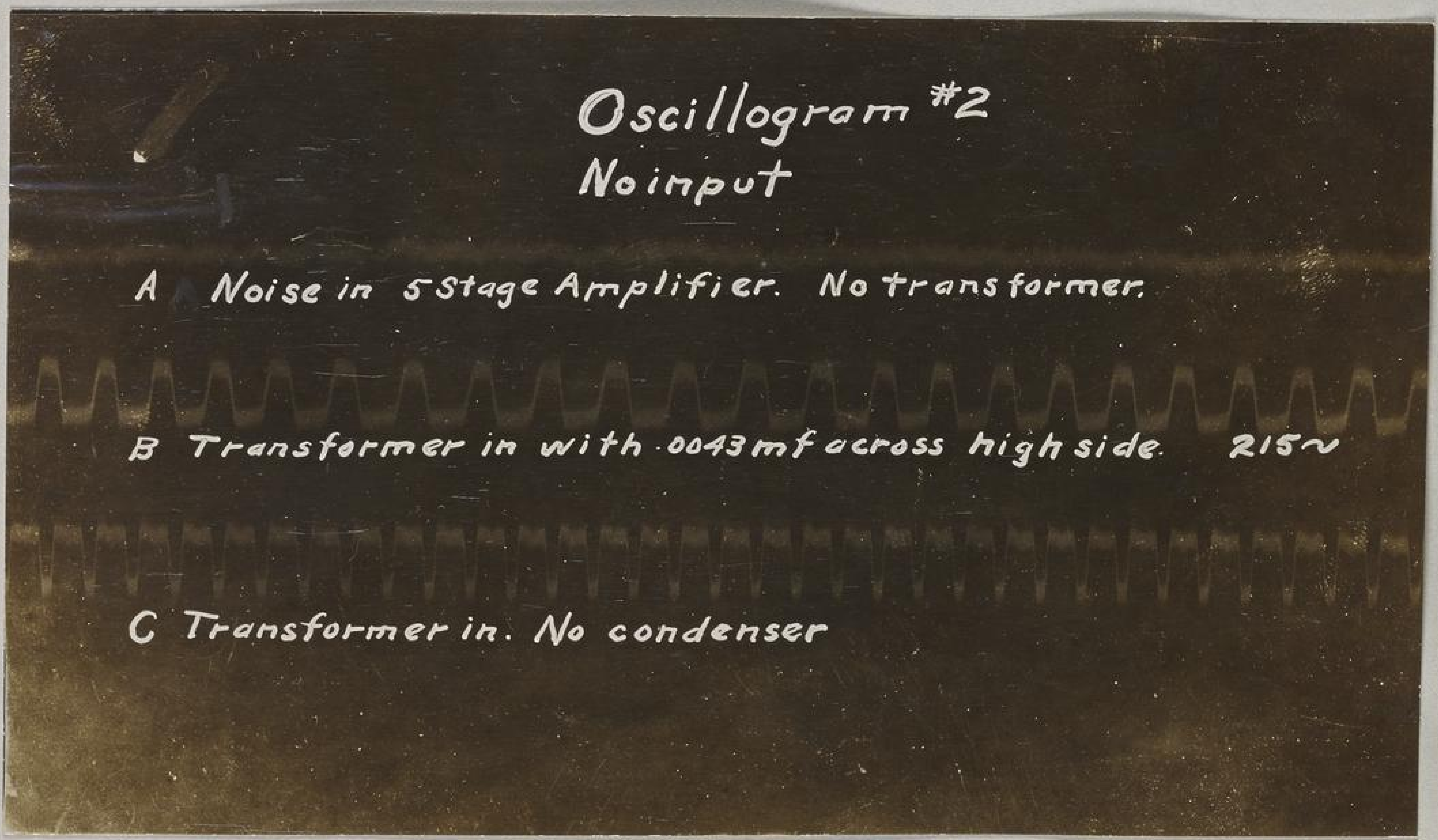
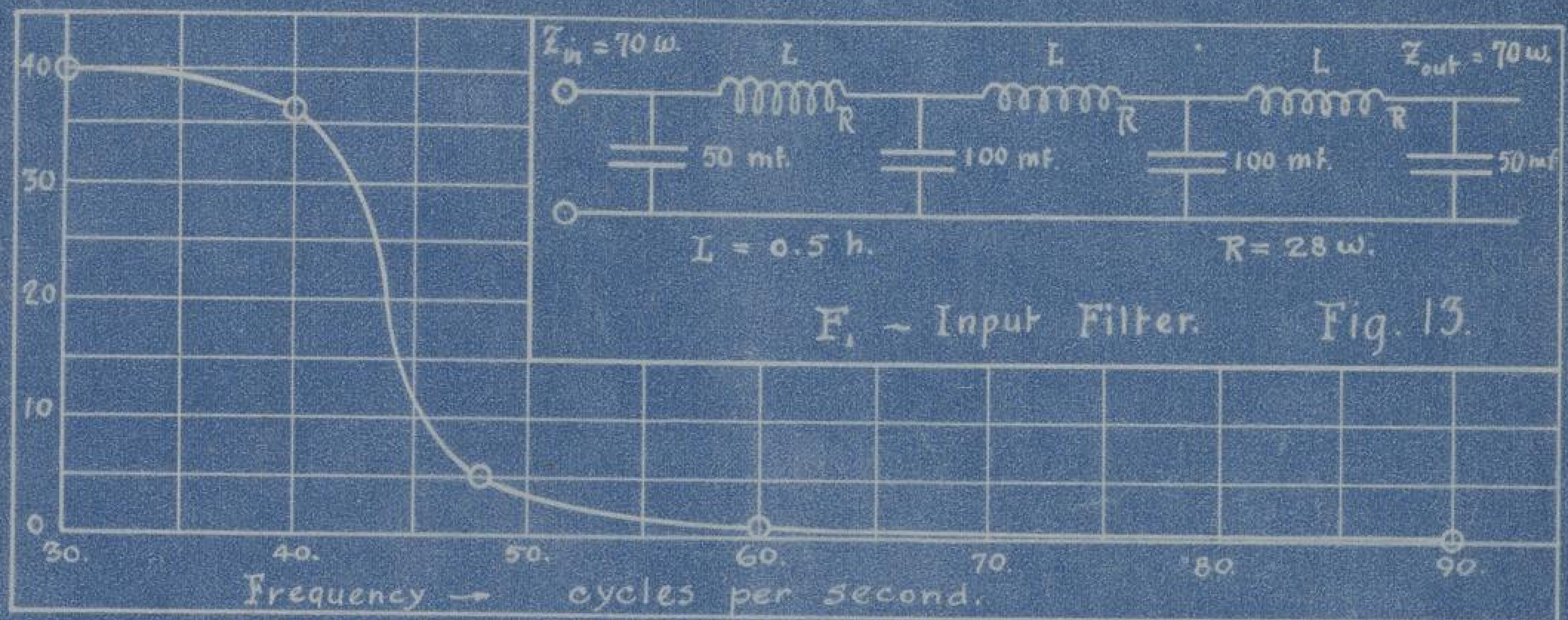
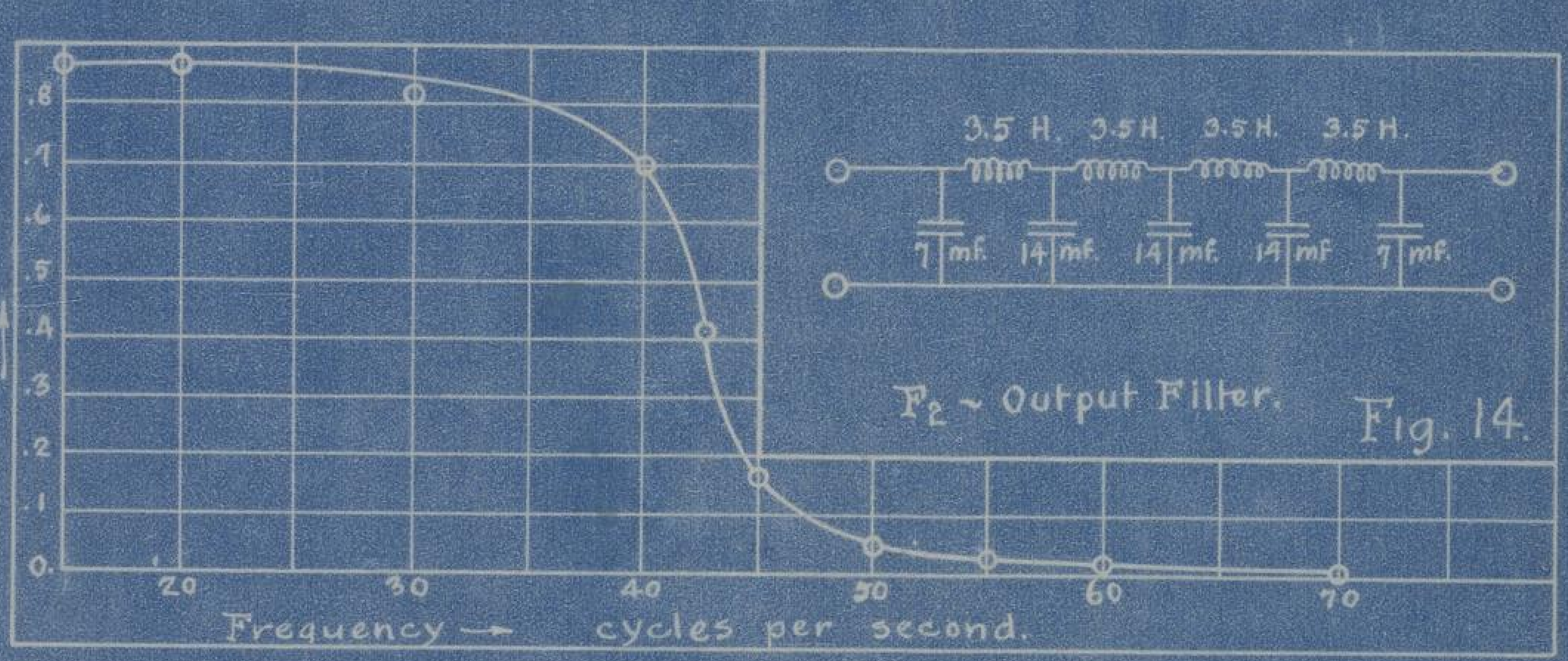

Oscillogram #2
No input
A Noise in 5 Stage Amplifier. No transformer.
B Transformer in with .0043 mf across high side. 215~
C Transformer in. No condenser

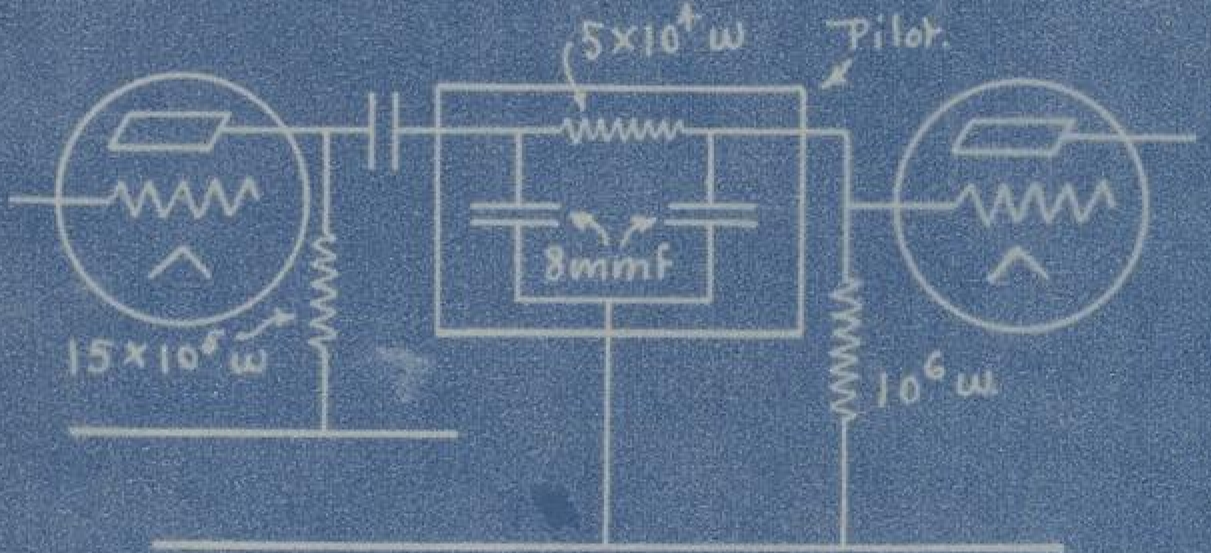
Fig. 11.



F₁ ~ Input Filter. Fig. 13.

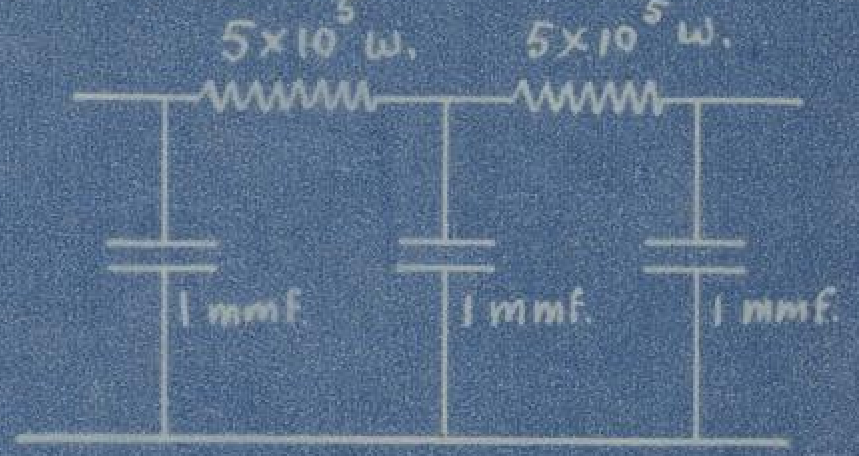


F₂ ~ Output Filter. Fig. 14.



~ Pilot Conductor as connected between Stages of Amplifier. ~

Fig. 15.



~ High Impedance Pilot Conductor. ~

Fig. 16.

In the experiments on shore the filters were found to be very effective in improving the conditions of balance. They cut out the higher frequencies, in accordance with the curves of Figures 13 and 14 and do not seriously impair the sensitivity. They do, however, pick up inductive disturbances in the same way as that described for the input transformer. On land it was possible to eliminate these disturbances by proper location and orientation of the filters. On shipboard these preventive measures could not be readily carried out, owing to the limitations of space and the irregular distribution of the various sources of electric and magnetic disturbance. Consequently, in the final experiments on shipboard no filters were used.

The pilot conductors greatly improved the conditions of balance in the galvanometer circuit. There was, however, at the same time, a great loss in sensitivity on account of their high impedance. Extensive experiments were carried out with various forms of pilot conductor and invariably with the same result. It is impossible to state whether the improvement of the balance was due to the elimination of troublesome disturbances rather than to the reduction of the sensitivity.

OVERLOADING OF AMPLIFIER.

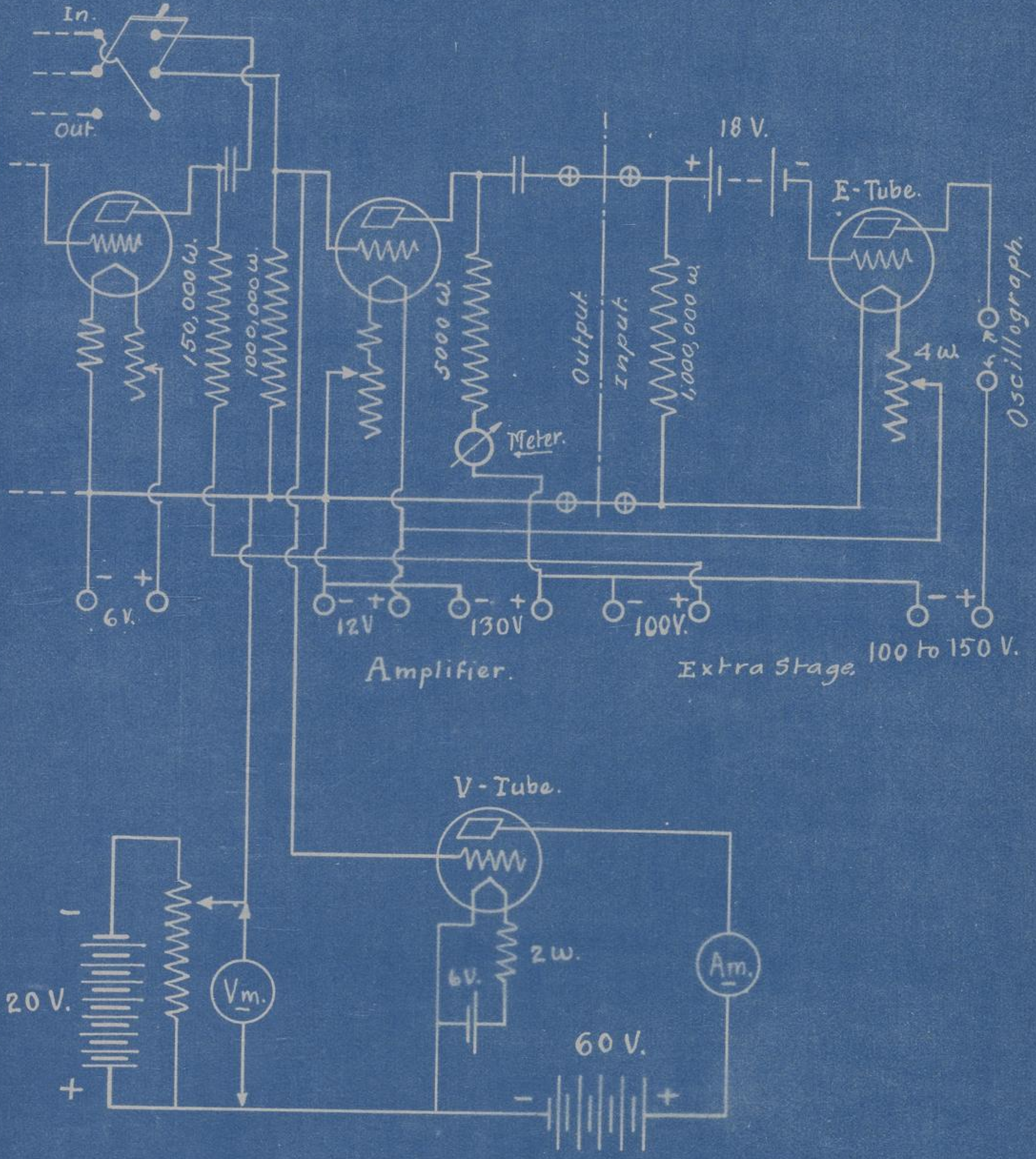
It is sometimes possible to balance the system so far as the 30 cycle detection signal is concerned and yet have present high frequency disturbances which do not appear in the balance other than as rapid vibrations of the needle about its zero position, with an amplitude say of three or four scale divisions. Under these circumstances it will sometimes be found that in passing from 3 to 4 stages, there is little or no increase of amplification. The explanation lies in the fact that at three stages the last tube of the amplifier has reached or passed its maximum rated load, the loading being caused by the amplified disturbance.

The value of the voltage on the grid is used as a measure of its condition as regards load. Thus, in normal operation the voltage on the grid of the last tube should not exceed 5 volts. This represents the limit of variation, beyond which the process of amplification will not take place. In studying the conditions in the amplifier circuit and in tracing and eliminating sources of disturbance, it therefore becomes very important to know the condition of load in the last tube. Disturbances of moderate value in the detecting circuit are often, in the use of 4 stages, amplified sufficiently to greatly overload the last tube and therefore curtail the amplification of the signal which is sought.

The conditions of overload in the last tube may be studied by means of the vacuum tube voltmeter, shown in Figure 17. This is an extra stage, consisting of a low impedance tube with an ammeter in the plate circuit, and the grid of which is excited by the same electromotive force as that feeding into the stage to be investigated. The connection to the low impedance tube, however, has inserted in it a set of batteries in opposition, the voltage of which may be varied and read. The reading is taken by adjusting this battery voltage until the plate-filament current in the vacuum tube voltmeter is zero. The voltage of the battery then gives the value of the voltage which is being impressed on the grid of the last stage. The operation will be evident from a study of Figure 17.

By means of a second low impedance stage, also shown in Fig. 17, or by use of the output transformer, it is possible to connect an oscillograph to the output and so study the wave form of any obscure disturbance.

In the experiments on land, some time was devoted to an effort to secure the maximum possible degree of amplification which might be



~ Vacuum Tube Voltmeter. ~

~ Fig. 17 ~

Extra Amplifier Stages.

used by studying and screening out, as far as possible, by the methods mentioned above, all disturbances. The results of this study can only be mentioned here. The principal disturbances were:

(1) "Noise" in the amplifier. (See oscillogram 2-a, fig.11). This was reduced by soldering all connections more carefully and overhauling ground connections and limiting the vibration of the amplifier.

(2) A high frequency periodic disturbance probably due to commutation in the continuous current power supply. This was filtered out. (See oscillogram 2-b, fig. 11).

(3) A variable 30 cycle disturbance, originating in the speed regulating circuit. This was reduced by a screening and orienting the tuning fork and the auxiliary rotary converter. (See Appendix D).

(4) A 60 cycle disturbance which was found to originate in the continuous current supply. This could sometimes be filtered out, but was finally removed by bringing a coil, inserted in the continuous current supply circuit, into inductive relation with the detecting coil and so orienting it as to kill the original disturbance.

The best conditions of balance without corresponding loss of sensitivity were always obtained by careful removal of causes of disturbance, identified in the ways just described. Obscure high frequency disturbances were still further removed by shunting a condenser of .0043 microfarads across the input of the amplifier. In this position the condenser is shunted across the high impedance secondary of the input transformer, a combination which constitutes a fairly efficient "low pass" filter.

Under the best conditions on shore, and with careful attention to all sources of disturbance, it was possible to obtain a balance

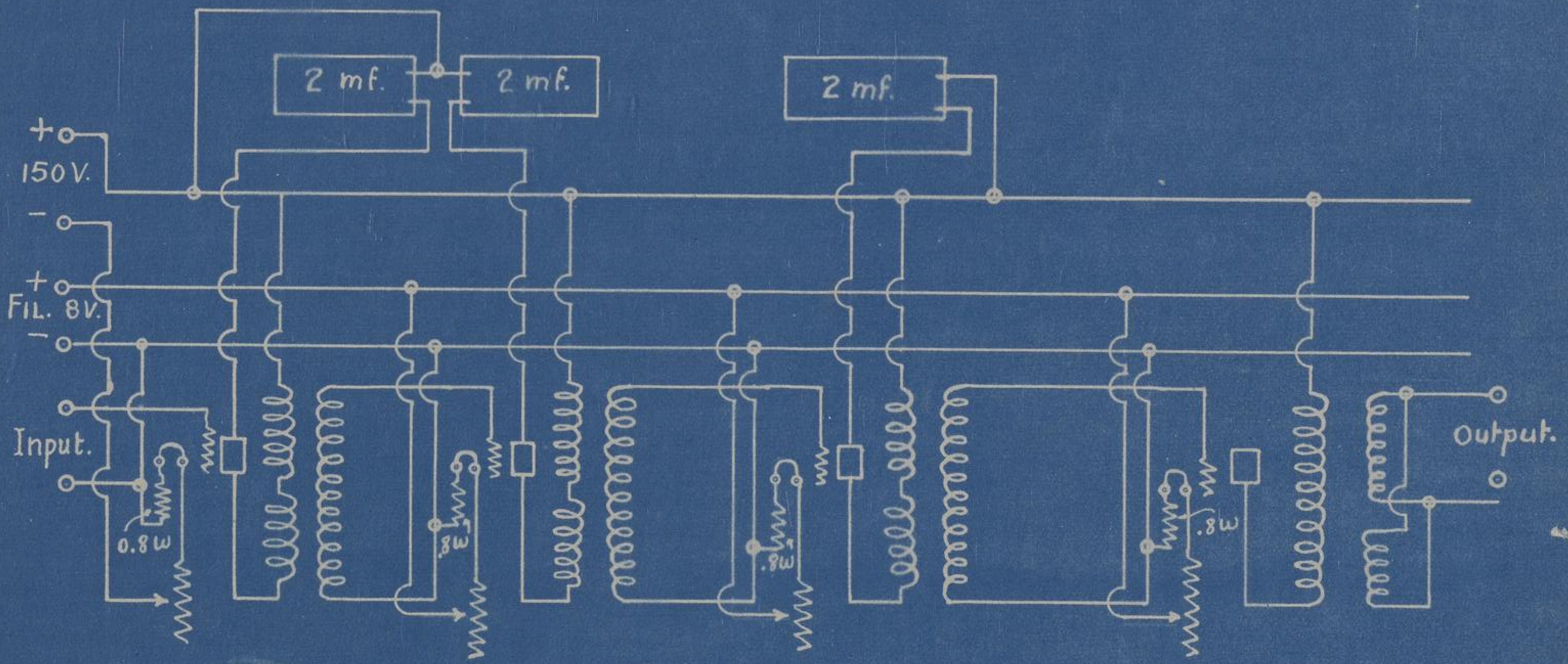
using four stages of amplification and the input transformer, or five stages without the transformer. These balances were so sensitive and susceptible that they were obviously unsuited for work on shipboard. They were therefore not used for taking detection observations for use as a basis in computing results in practice.

CONDITIONS ON SHIPBOARD.

As anticipated, the conditions on shipboard were radically different from those encountered in the earlier work. Two most serious disturbances were those due to the vibration of the boat, caused by the engines, and the change in relative position of the magnet and the detecting coil, due to the straining of the hull of the ship. The effect of vibrations of the engines was considerably reduced by supporting the amplifier on springs. For these reasons it was found that the extreme value of amplification that could be used was four stages. As already mentioned, the input transformer was found to be unsuited to conditions aboard ship. The shunt to the galvanometer was also usually set much lower than 90 ohms and often as low as 10 ohms.

Under the above conditions, in quiet water and uniform speed, it was usually possible to secure a fair working balance. This balance, however, was invariably upset by sudden changes of speed, by rough water, or by a sharp change of course.

Toward the end of the experiments on board ship another amplifier with electro-magnetic coupling, as indicated in Figure 18, was used. This amplifier was not disturbed by a vibration of the boat to quite the same extent, apparently due to smaller, more compact, construction of the tube electrodes. This improvement was not however sufficiently great to permit an increased degree of amplification with resulting increase in the distance of detection.



– Fig. 18. –

30 Cycle Amplifier.

– Transformer Coupling. –

Vt 14 Pliotrons.

APPENDIX D.

REGULATION FOR CONSTANT SPEED.

Extreme constancy of speed is highly essential for maintaining the balance in the detecting circuit under conditions of high sensitivity.

REGULATION BY TUNING FORK.

The method of speed regulation which was used throughout the greater portion of the experiments is indicated in Figure 19. In this method the ultimate source of constant speed is an electrically operated tuning fork. A small rotary converter of the same frequency as the tuning fork is driven from the direct current end and is loaded with a resistance on the alternating current end, the load circuit being taken through a pair of contacts on the tuning fork, contact being made once during each half wave. The time interval of contact on the tuning fork is a fraction of the whole alternating current period. If the speed rises, contact is made at an instant when there is a greater electromotive force and current, thus resulting in a greater load on the converter. If the speed goes down, the conditions are reversed, consequently the tendency of the change of load is to maintain the speed of the converter constant. This tendency can be made greater or more positive by inserting resistance in the armature circuit of the continuous current end of the converter.

The shaft of the small converter and that of the larger machine which is to be controlled are each supplied with a crown commutator. The number of commutator segments for each is chosen so that by their speeds the frequencies of reversal of the two commutators are the same. For example, in the experiments on S. C. #326, the speed of the generator for exciting the magnet was 1/2 that of the regulating converter, consequently the numbers of commutator segments in the

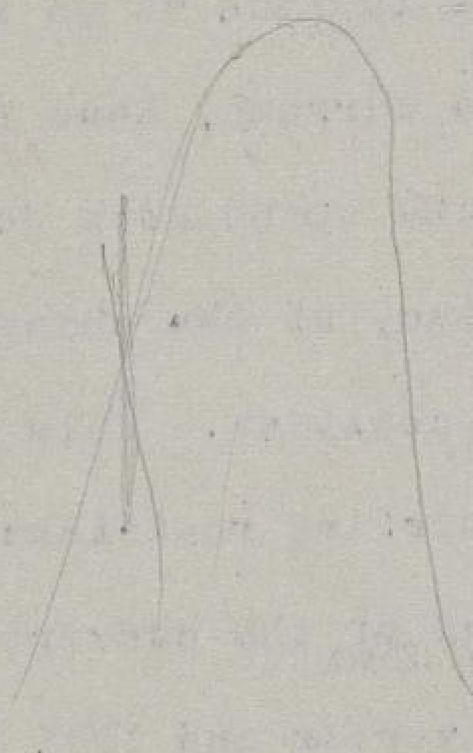


Fig. 19.

~ Tuning Fork Speed Control. ~

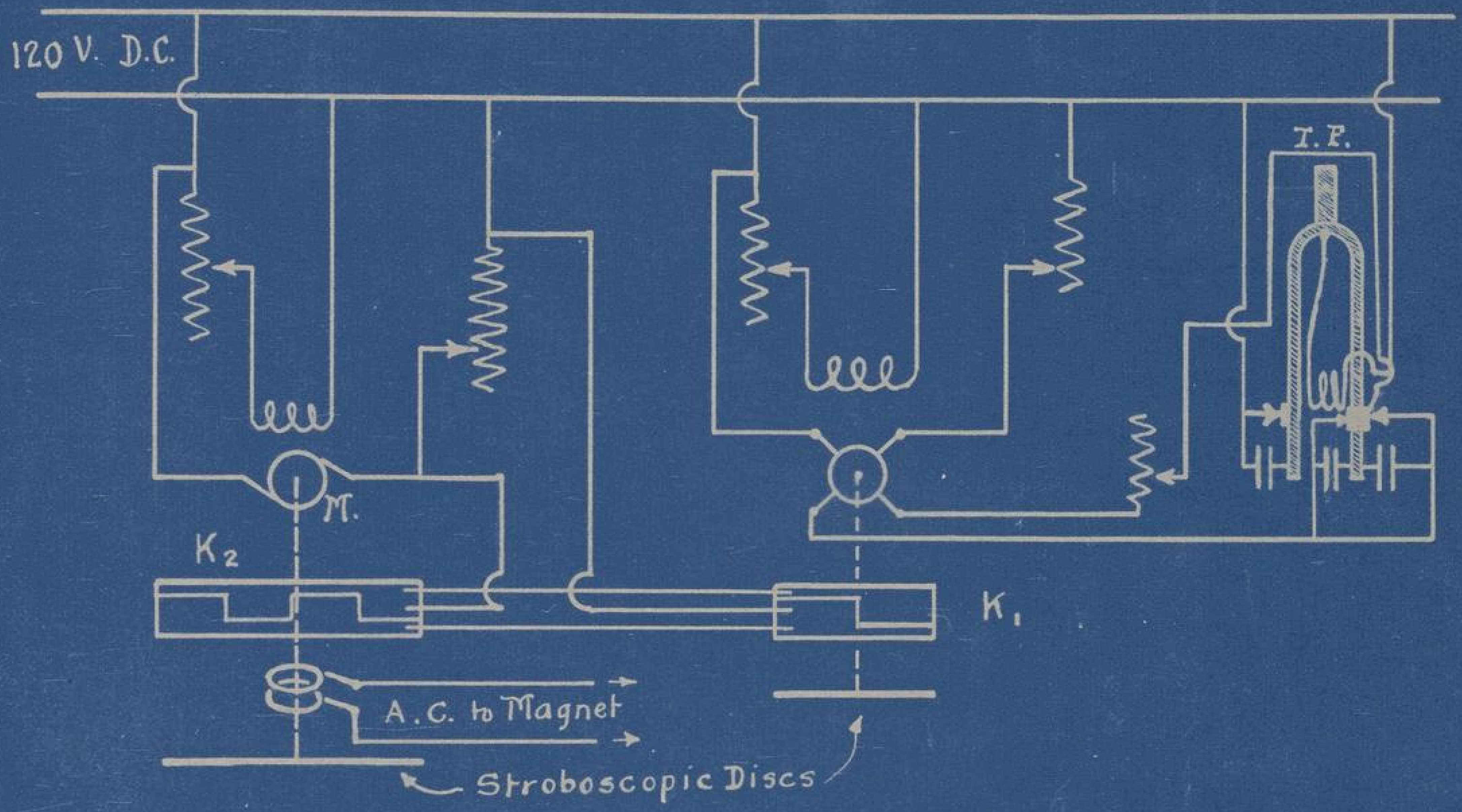
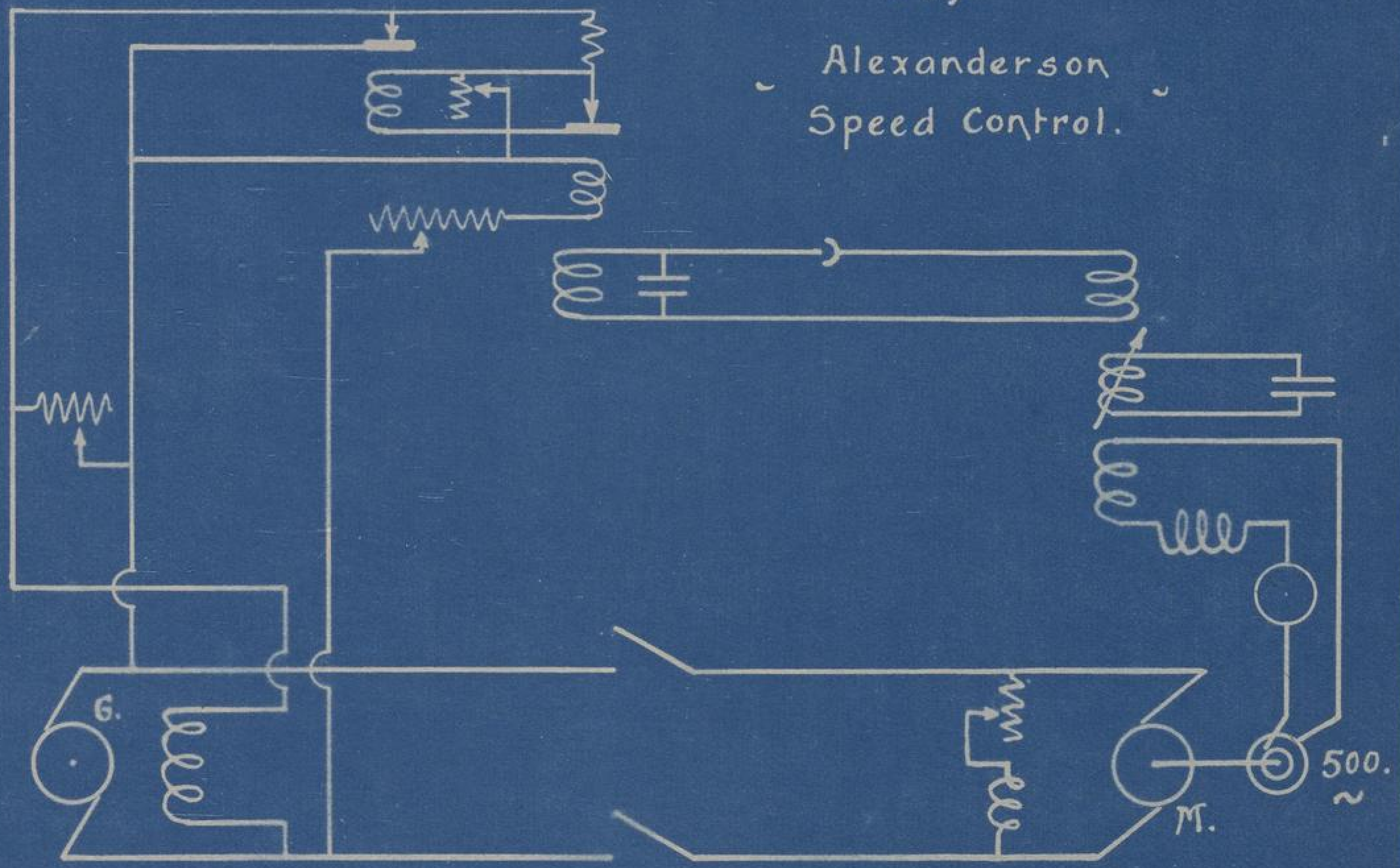


Fig. 20.

~ Alexanderson Speed Control. ~



respective cases were 4 and 2. The commutators were connected together, as indicated in Fig. 19, in such a way as to short-circuit a small resistance in the armature circuit of the main driving motor for a greater or less period, according as the commutators depart more or less from the position of exact coincidence of phase. The machines automatically find such a relative commutator phase relation that an increase in speed decreases the duration of short-circuit of the armature resistance, and vice versa, so that the average voltage on the motor armature is such as to more or less exactly maintain the speed in a constant relation to that in the small converter, which in its turn is maintained constant by the tuning fork. The introduction of the small converter is necessary, since the tuning fork contacts will not carry the large currents interrupted in the control of the considerably larger direct current motor. The plan, as outlined, was used to control the speed of a 90 H.P., 230 volt, continuous current motor operating at about 40 H.P. The speed of this machine was maintained constant by this method to within approximately .5%.

A number of modifications of the above method were tried, but without equal success. Among them were the following:

(1) Apply a load to a small auxiliary alternating current generator, mounted on the shaft whose speed is to be controlled, interrupt the load of the alternator by the commutators, and thus regulating the speed in a manner similar to that in the combination of the small converter and tuning fork. The load necessary was found to be too great and the voltage between commutator segments too high, resulting in serious sparking.

(2) The commutators were used to short-circuit a resistance in the field circuit of the main driving motor, rather than in its armature circuit. It was thought that the smaller value of current in-

volved would result in an improvement in commutator action. However, the magnetic inertia of the field and the consequent slow action resulted in pronounced hunting of the larger machine.

ALEXANDERSON METHOD OF SPEED REGULATION.

On shipboard motion of the ship caused the armature of the small converter, described in the foregoing method, and also that of the main motor generator to shift in their bearings, resulting in variable friction, and consequently in irregular variations of speed. Ball thrust bearings improved conditions somewhat, but not completely. The following method, due to Mr. E. F. W. Alexanderson, of the General Electric Co., was, through the courtesy of Mr. Alexanderson, studied as adapted to our needs, and finally put into operation.

The method is indicated by the diagram of Figure 20. The essential features are a combination of an ordinary continuous voltage regulator with a resonant alternating current circuit. The resonant circuit is excited by a 500 cycle generator, geared to the shaft of the machine whose speed is to be controlled. The natural frequency of the tuning circuit is adjusted by variable reactance and capacity, so that the desired speed of the main generator is on the steep portion of the rising limb of the resonance curve. This circuit is loosely coupled to a circuit containing a vacuum tube rectifier and a part of one of the coils of the voltage regulator. When the speed rises for any reason, the current in the resonant circuit increases and thus operates the voltage regulator just as though there had been a rise in voltage. The regulator is therefore affected by either a rise in voltage or a change in speed, or both operating simultaneously. The 500 cycle generator was taken from an Army radio "pack set" and weighed only 40 lbs.

This method of speed control is very positive in action. The closeness of its control was tested by comparison with a tuning fork. By a system of mirrors the amplitude of the tuning fork vibration was greatly extended and a stroboscopic disk on the generator shaft permitted a close estimate of the momentary fluctuations of speed of the main generator shaft. These momentary variations were found not to exceed .04%.

Temperature, or other slow variations of conditions, will cause a slow change in speed with the Alexanderson apparatus. Such slow changes, however, are of relatively small importance in their bearing on the balance of the detecting circuit. Sudden changes of small duration are the most troublesome. The use of the Alexanderson method therefore greatly improved the conditions of balance.

The tuning fork method is free from the slow changes due to temperature, and it appears that a further refinement in speed control might be possible by using both the tuning fork control and the Alexanderson control on the same shaft.

APPENDIX E.

CHOICE OF FREQUENCY.

Early in the work at Baltimore a study was made, with a number of experimental submarine models, on the sensitivity of detection as affected by the alternating frequency. Some of the results are shown in Figure 21 and Table 8.

The curves indicate that for every thickness tried there is a frequency at which the deflection of the detecting instrument for a given distance of the submarine is a maximum. These curves were all taken with approximately constant flux in the magnet.

With a given strength of field at the submarine, due to its magnetisation the electromotive force in the detecting coil rises with the frequency. The influence of secondary currents and eddy currents set up in the hull, however, also increases with the frequency, thus resulting in an increasing demagnetising effect. The resultant maximum may therefore be due to the preponderance of the former effect at the low frequency, and of the latter effect at the high frequency.

With increasing thickness of the submarine, as indicated by the curves, the maximum of detection signal tends toward lower frequencies. (See curve a, Fig. 21, showing relation of thickness and maximum deflection). For the thickest submarine the maximum is also more sharply marked.

The earlier experiments with submarine models of the smaller thicknesses had indicated 30 cycles as the region of maximum sensitivity. The latter experiments, above described, rather indicate that a still lower frequency might be better suited for service in actual practice in which the thickness is greater. However, the relative distances and strengths of field at submarine and coil were different in several instances, thus introducing factors which are necessarily

- Fig 21. -

~ Effect of Frequency on Sensitivity. ~

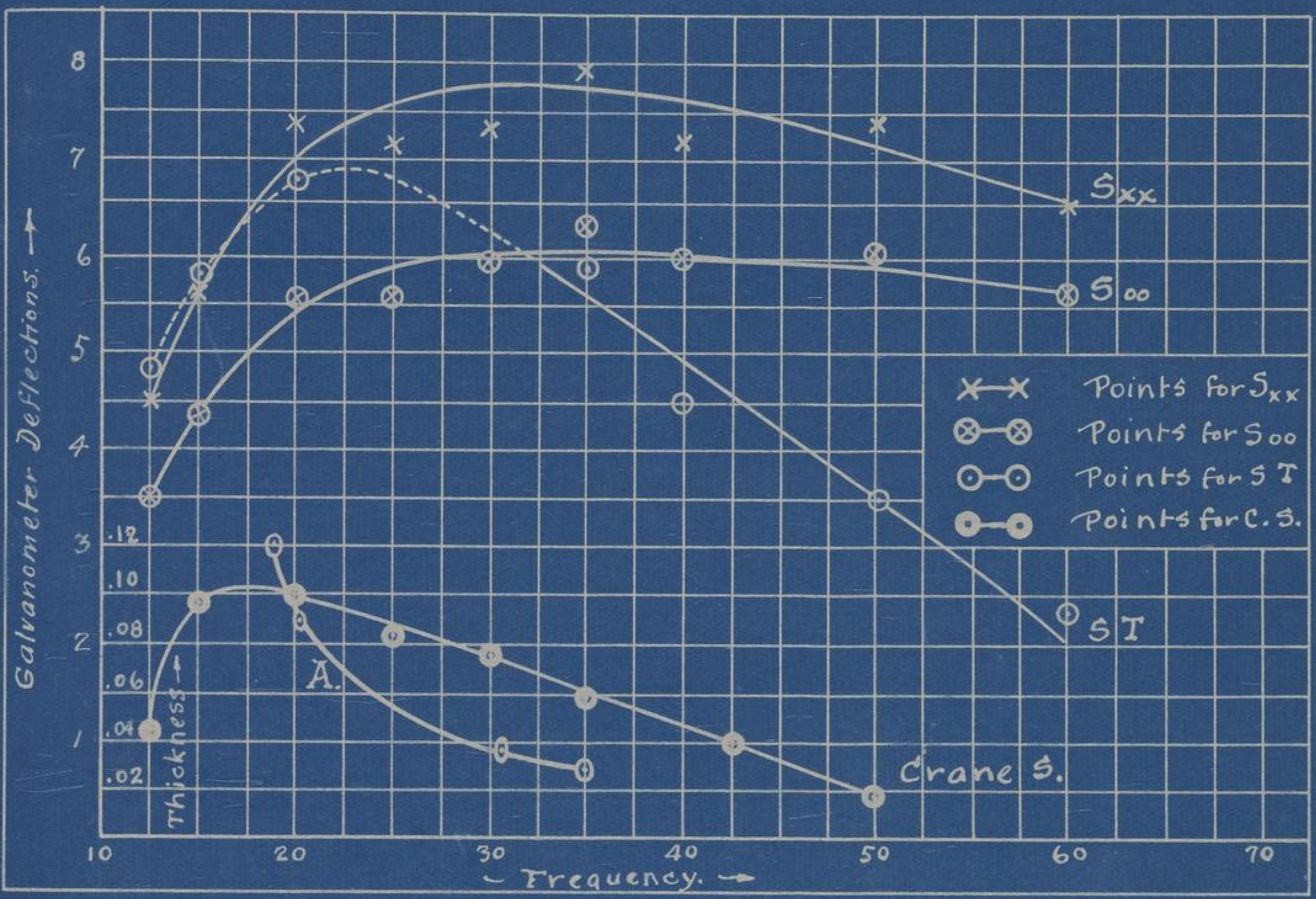


Table 8.

Freq.	Volts.	Amp.	- Deflection at 9 ft. -			Defl. at 12'. Crane S.
			S_{oo}	S_{xx}	T.	
12.	10.1	2.56	3.47	4.50	4.70	1.18
15.	12.5	2.74	4.40	5.65	5.80	2.45
20.3	18.2	3.00	5.60	7.40	6.90	2.50
25.	20.7	2.79	5.57	7.21	6.16	2.76
30.	25.0	2.81	5.95	7.35	5.80	1.77
35.	29.1	2.78	6.30	7.90	6.00	1.35
40	33.4	2.83	6.05	7.20	4.50	1.10
50	41.6	2.80	6.15	7.30	3.45	0.50
60	50.2	2.80	5.70	6.50	2.70	——

uncertain and which might therefore upset this conclusion. In any event, as indicated by the curves, there is relatively small gain in sensitivity in going from 30 cycles to say 15 cycles. As machines and other equipment adapted to 30 cycles were readily available, and those of lower frequency not obtainable within a reasonable time, the experiments were continued at 30 cycles.

APPENDIX F.

TESTS OF FORMULA 11.

The relations shown in Formula (11) were tested in the laboratory in an extensive series of experiments. Model submarines of different lengths, diameters, thicknesses and material were tried under as nearly as possible the same conditions. In addition, the inverse sixth power of Formula (10) was tested. No attempt will be made to include a complete account of these experiments here. The general results only will be given.

Formulae (10) and (11), for computing the distance of detection, show that if D is small compared with d, the signal should be inversely proportional to the sixth power of d. When D has a value that is more nearly comparable with the value of d, the increase of the signal with the decrease of d is proportional to some higher power of d.

The conclusion of the foregoing paragraph was readily tested by reading the variation of the signal in the detecting instrument with the approach of the submarine. With D equal to 5 ft. 8 in. and d decreasing from 15 ft., the signals were found to vary with approximately the inverse eighth power of d over the relatively short distance in which the comparison could be made. When D was reduced to 2 ft. or less, the average of a number of runs showed that the signal varied inversely as d to the power 6.2. A number of similar tests, all made with arrangement A of Figure 1, indicated that the inverse sixth power was approached the smaller the value of D.

The tests as to the variation of the dimensions of the model were made with three models of the same size as S_0, but of different thicknesses, namely, .025 in., .0375 in. and .0625 in., and also with two models of different diameters, as well as different thicknesses.

All were separable into several sections. (See Tables 9, 10 and 11).

The influence of the length of the model on the signal is given in Table 9. The average ratio of the lengths in the comparisons which are recorded is 2.06. The corresponding average of the ratio of the signals is 1.72. The curve of Figure 22 shows clearly that when the length of the submarine is comparable with d, its effective length as a magnet decreases rapidly with the distance from the main magnet. It is therefore to be expected that this ratio, as observed on sections of varying length, should be lower than the ratio of the actual lengths. The last line in the table gives an exaggerated case of difference in the comparison of a 10 ft. submarine with a 16 ft. submarine. The ratio of signals is 1.14. This instance has not been included in taking the average mentioned above.

The influence of the diameter of the model is shown by the results of Table 10. The average of a number of tests indicated that the signal increases directly as the diameter, the ratio of the diameters being 2 and the average ratio of the signals being 1.91.

The results of a study of the influence of the thickness of the wall of the model, shown in Table 11, are not so definite. The ratio of thicknesses of wall is in two cases 2.5. For the submarine of 1 ft. diameter the average ratio of signals was 1.92, but that for models 2 ft. in diameter the ratio was only 1.13. A possible explanation may lie in the greater demagnetising influence in circulating and eddy currents in the case of the model having larger diameter and greater thickness. The conclusion here is obviously not definite, but indicates at least some increase of signal of detection with increasing thickness of the shell of the submarine. It should be borne in mind, in all tests of this character, that there is a great element of uncertainty as to the continuity of the magnetic structure of an

Table 9.

~ Influence of Length of Submarine. ~

Length	Signal.		Length.	Signal.		Diam.	Thickness	Ratio of Lengths.	Ratio of Signals.	
	d = 15'	d = 12'		d = 15'.	d = 12'.				d = 15'.	d = 12'.
96"	3.35	17.5	70"	2.82	15.4	1'	0".0625	1.37	1.19	1.14
96"	3.35	17.5	35½"	1.08	8.03	1'	.0625	2.71	3.10	2.18
70"	2.82	15.4	35½"	1.08	8.03	1'	.0625	1.97	2.61	1.92
96"	1.75	8.2	69½"	1.35	7.6	1'	.025	1.38	1.30	1.08
69½"	1.35	7.6	36"	.80	4.1	1'	.025	1.93	1.69	1.85
96"	1.75	8.2	36"	.80	4.1	1'	.025	2.67	2.19	2.00
84"	3.97	23.0	55"	2.70	18.5	2'	.0625	1.56	1.47	1.24
55"	2.70	18.5	30"	1.85	12.4	2'	.0625	1.83	1.46	1.49
84"	3.97	23.0	30"	1.85	12.4	2'.	.0625	2.80	2.15	1.86
56"	2.35	15.3	28"	1.80	10.7	2'	.025	2.02	1.31	1.43
84"	3.65	18.9	56"	2.35	15.3	2'	.025	1.50	1.51	1.24
84"	3.65	18.9	28"	1.80	10.7	2'	.025	2.03	2.03	1.77
16 ft.	3.90	—	10 ft.	3.43	—	1'	.025	1.6	1.14	—

Table 10, Influence of Diameter.

Ratio of Diameters = 2.

← Signal →				Ratio of Signals.	
d = 15'	d = 12'	d = 15'	d = 12'	d = 15'	d = 12'
3.82	18.6	1.73	7.85	2.21	2.37
3.35	17.5	4.20	22.3	1.26	1.28
2.82	15.4	2.70	18.5	1.22	1.53
1.08	8.03	1.85	12.4	2.03	1.83
3.35	17.5	3.97	23.0	1.36	1.50
1.80	10.7	.80	4.1	2.92	3.39
2.35	15.3	1.35	7.6	2.16	2.50
3.65	18.9	1.75	8.2	2.38	2.64
3.35	17.5	3.97	23.0	1.36	1.50
2.82	15.4	2.70	18.5	1.24	1.53
1.08	8.03	1.85	12.4	2.03	1.83

Table 11. Influence of Thickness.

Ratio of Thicknesses = 2.5

Diameter.	← Signal →				Ratio of Signals	
	.0625		.025			
	d = 15'	d = 12'	d = 15'	d = 12'	d = 15'.	d = 12'.
1'	3.35	17.5	1.75	8.2	1.91	2.14
1'	2.82	15.4	1.35	7.6	2.09	2.03
1'	1.08	8.03	.80	4.1	1.37	1.99
2'	3.82	18.6	4.2	22.3	1.10	1.20
2'	1.80	10.7	1.85	12.4	.95	1.07
2'	2.35	15.3	2.7	18.5	1.17	1.23
2'	3.65	18.9	3.97	23.0	1.09	1.22

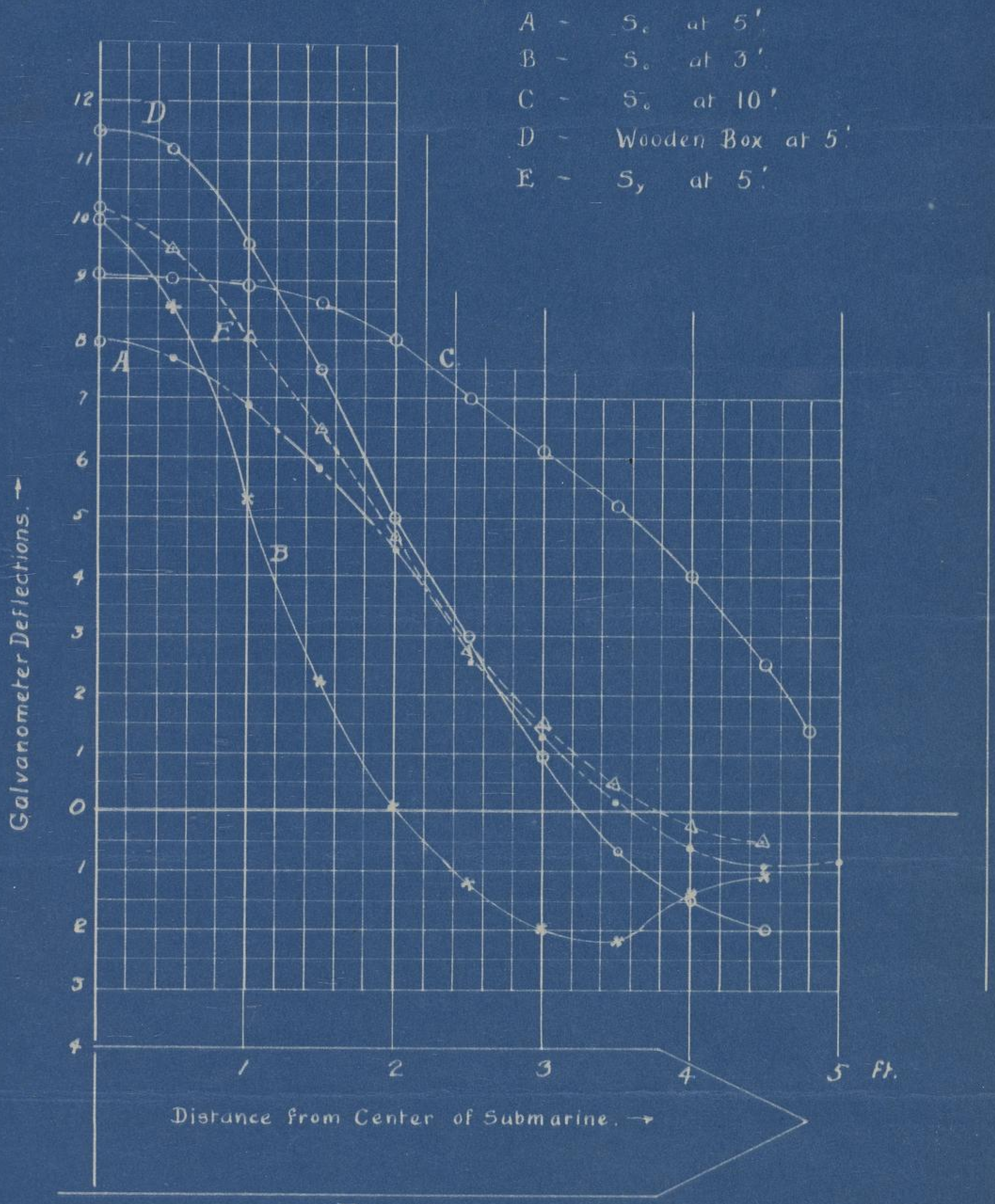


Fig. 22.

~ Magnetization of Submarine. ~

Homewood

actual submarine. It seems quite possible that the caulking and painting of the plates may well interpose non-magnetic layers which would seriously offset the simple relations which are assumed in Formula (11). It was clearly recognized, through all the work of this character, that the experimental conditions probably differed markedly from those which would actually obtain in the case of the application to full size submarine. On the other hand, it appeared a matter of considerable importance that the approximate relations of the formula should be tested.

By the method of derivation of Formula (11), it is shown that the distance of detection, using arrangement B of Figure 1, should be greater than that of arrangement A by a factor the sixth root of 4, that is, 1.26. Owing to the limited distance of detection in the laboratory experiments, there are few possibilities for a convenient and certain test of this relation. From a number of tests in this direction only one will be given here:

Arrangement A. Distance for a standard signal - 11.25 ft.

Arrangement B. Distance for the same signal - 15 ft.

The ratio of these two distances is 1.33, indicating that the actual sensitivity of arrangement B, as compared with arrangement A, is greater than indicated by theory.

There appeared to be no reason why tests of this character should be extended further to a more careful determination. The object of all of this work was to check, to only an approximate degree, the relations of Formula (11), so that they might be used as a basis for the design of larger equipment.

APPENDIX G.

ELECTRICAL BALANCE IN THE DETECTING CIRCUIT.

A question which arose early in the laboratory tests was the proper setting of the commutator for the maximum signal in the detecting coil due to the magnetised submarine. This question was answered experimentally by taking a number of detection observations with different commutator settings. A balance was obtained for each setting by rotating the balance coil C', the detecting coil remaining fixed, and then bringing up the model submarine to a definite standard position. The conclusion from these experiments was that the phase of the signal from the submarine is practically co-incident with that from the main magnetic field due to the magnet, and that therefore the proper commutator setting for the submarine signal was the same as that pertaining to the electromotive force induced in the detecting coil by the magnetic field of the magnet. This conclusion was subsequently checked in the experiments afloat by making detection observations for different commutator settings. The simplest steps for obtaining a balance then are: to set the detecting coil with its plane approximately normal to the magnetic field, to cut out the balancing coil or rotate it until its plane is approximately parallel to the field, to insert a high non-inductive resistance in the detecting circuit in order to limit the current in the detecting instrument, inductance being already balanced with capacity, and then to rotate the brushes around the commutator to a point where the galvanometer deflection is zero. At this setting the current in the detecting circuit is chopped up into equal positive and negative quarter-waves. The commutator is then rotated 90 electrical degrees, in which position it will indicate, to a maximum degree, all disturbances in the detecting circuit which are in phase with the electromotive force induced in the detecting coil by the main field.

The non-inductive resistance is now cut out, the balancing coil inserted and rotated to give a balance, as indicated by the detecting instrument.

In the early experiments, before the amplifier was used, it was found possible to obtain a very satisfactory balance with the above method, using a D'Arsonval suspension galvanometer of 83 megohms sensitivity, and the experiments of the type recorded on page 14 were taken under these conditions, but even at this time it was obvious that there were disturbances in the detecting system which could not be eliminated by the simple operations of commutator setting and rotating the balancing coil. At this point there began a study of the conditions of balance in the detecting circuit which extended through the entire period of the work, both ashore and afloat. With increasing sensitivity in the detecting circuit, there always appeared new types of disturbance which had to be attacked and, as far as possible, eliminated. In fact, the one problem in increasing the distance of detection is to increase the sensitivity of the detecting circuit, as shown in Figure 2, without at the same time permitting the entrance of many types of common disturbance which are normally of greater magnitude than the signal due to the submarine.

Along with the various steps in the increase of the sensitivity, there was a continuous process of refinement of electric and magnetic screening and the rigid fastening of all leads and coil supports in the detecting circuit. It was found that this circuit must be grounded at one single point. If there are two grounds connected by a single stretch of wire in this circuit, under conditions of high sensitivity enough difference of potential arises to mask the signal.

Disturbances of the position of the galvanometer needle about its zero naturally led to studies of the commutator and of changes in

voltage and frequency in their influence on the magnet excitation. The development of the commutator finally led to a rigid mounting on the end of the generator shaft, careful machine construction with narrow mica insulation between segments, and to quite narrow brushes with light spring tension. These brushes were usually made of three layers of brush copper with a thin steel backing for the spring tension. The commutator was kept clean by a rather sparing application, once or twice a day, of high grade lubricating oil, with a clean rag.

Variations of both frequency and of voltage were found at once to upset the balance very violently. It became evident that the greater portion of the disturbances were due to these causes, especially to frequency variation. Efforts were directed not only to obtain constancy in these particulars, but also to a study of the possibility of compensating in some way the disturbances themselves. Since constancy of frequency is only a relative term,it is obvious that with increasing sensitivity possible disturbances, due to frequency variations, will continually appear.

If the system without amplifier is balanced, as described above, and the commutator be then rotated to successive positions, it will be found that the balance is upset, showing the presence of a residual disturbance in the detecting circuit after it is balanced. The wave form of this disturbance may be taken and while it is distorted in shape, its principal component is that of the fundamental 30 cycle frequency, thus showing the presence of an electromotive force which is displaced 90 degrees from that induced by the main field. This led to the question of a difference in phase in the electromotive forces in the detecting and balancing coils, and an experimental study promptly revealed the fact that with increasing distance from the magnet there was a continual lag in phase of the main magnetic field. It was

subsequently found that this condition obtained with all three of the magnets. In the case of the laboratory magnet, M_1, for example, there was a lag of 4.5 electrical degrees in moving the detecting coil from a distance 4 ft. to a distance 17 ft. from the magnet. This residual may be balanced out in a number of ways, as described below, and in this way it was found that the disturbance due to frequency variation is very greatly reduced, and that due to voltage variation practically disappears when this residual is completely balanced out.

Two of the earliest efforts to balance out the residual electromotive force, due to the difference in phase in the electromotive forces in the detecting and balancing coil, should be described. In the first of these, the electromotive force in the detecting coil was balanced by a few turns taken completely around the main magnet, the process of balancing being accomplished by rotating the detecting coil. It was found that by moving the balancing coil to different positions on the magnet, a place could be found for which a given change in frequency or voltage could be compensated; i. e., on making this change there would be no upset of the zero reading of the detecting instrument. The second method involved moving a balancing coil to different positions in the neighborhood of the magnet in an effort to find a position in which the phase of the electromotive force in this coil was co-incident with that in the detecting coil. Sometimes this position could be found with resulting great improvement in the balance. Neither of these arrangements was satisfactory, the first because it compensated only for frequency and voltage changes of definite magnitude, and the second because the position described could not always be found.

The introduction of the amplifier greatly accentuated the influence of the residual electromotive force in the detecting circuit.

Its presence became immediately evident in the balanced condition by a 60 cycle vibration of the galvanometer needle. The amplitude of this vibration would be normally two or three divisions of scale and thus became a ready means of determining the presence of a residual electromotive force. The vibration, or "wiggle", of the needle is obviously caused by the chopping up of the 30 cycle residual at its maximum point, since the commutator is set for a disturbance differing in phase from it by 90 electrical degrees.

METHODS OF ELIMINATING RESIDUAL ELECTROMOTIVE FORCE.

Following is a list of some of the methods which were tried for eliminating the residual electromotive force in the detecting circuit.

(1) Shunt the balancing coil with a non-inductive resistance, so that the electromotive force in the terminals of this resistance is in phase with the electromotive force in the detecting coil. (See Fig. 2). This was the method finally adopted. The coil is rotated for balancing.

(2) Introduce into the detecting circuit an electromotive force derived from the circuit exciting the magnet:

- (a) By resistance in series with the magnet winding, (Fig. 23).
- (b) Inductively from a coil in series with the magnet winding and acting on the balancing coil.
- (c) Inductively from a coil excited by connection across a resistance in series with the magnet winding and acting on the balancing coil.
- (d) Inductively from a coil in parallel with the magnet winding.
- (e) Inductively from a coil excited from the terminals of the balancing coil.

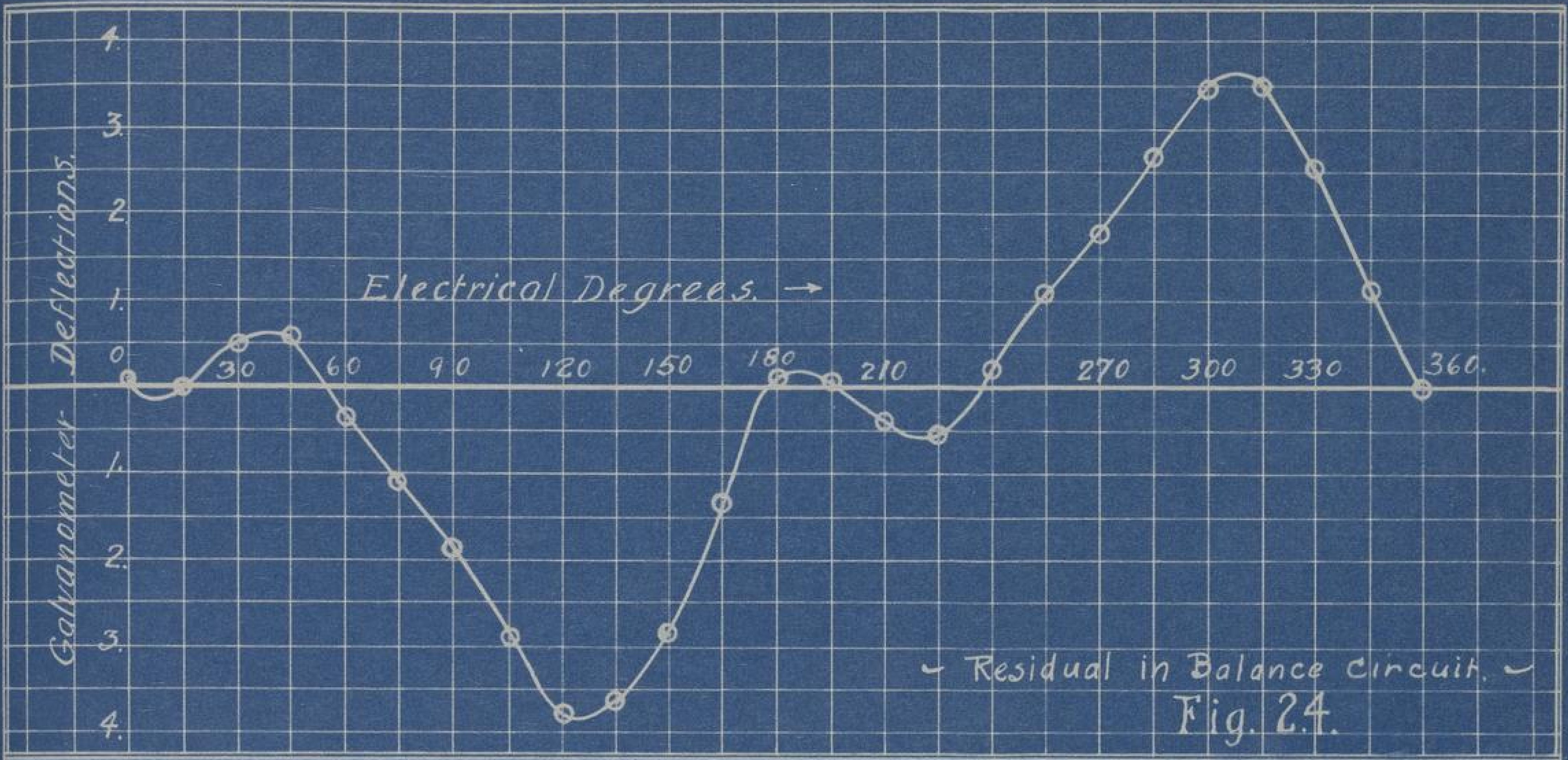


Fig. 24.

Fig. 23.

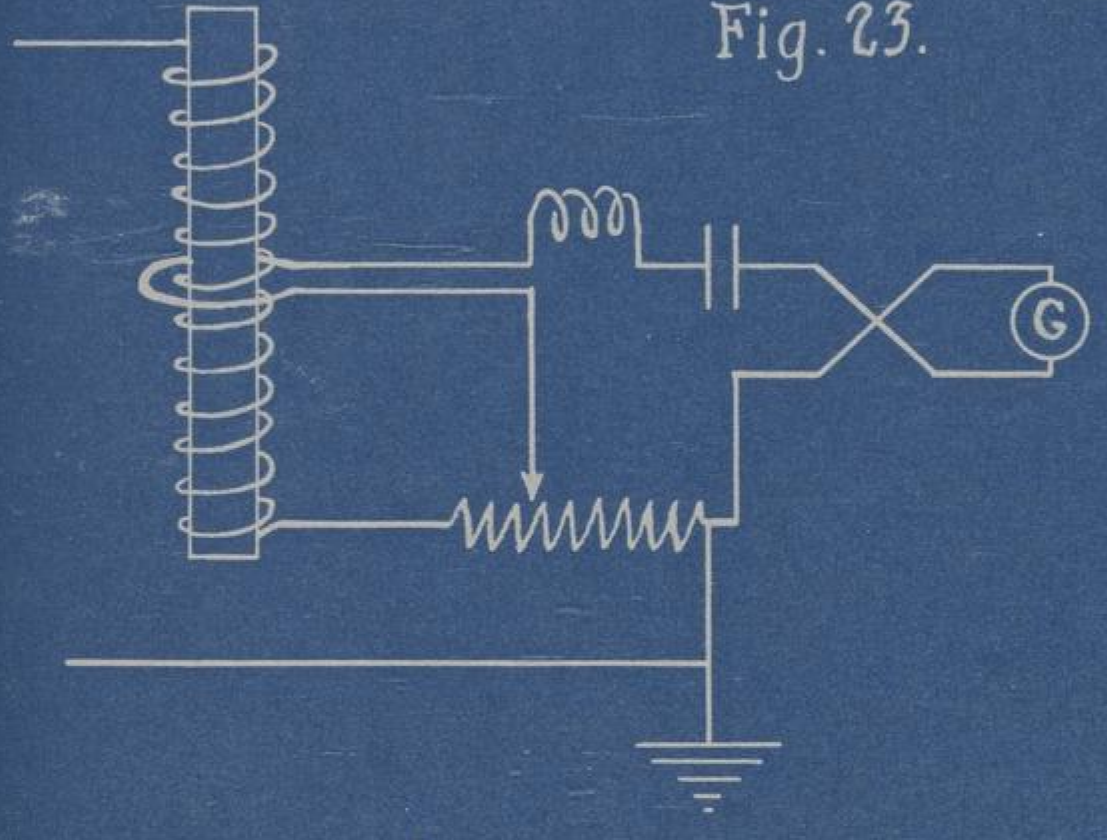
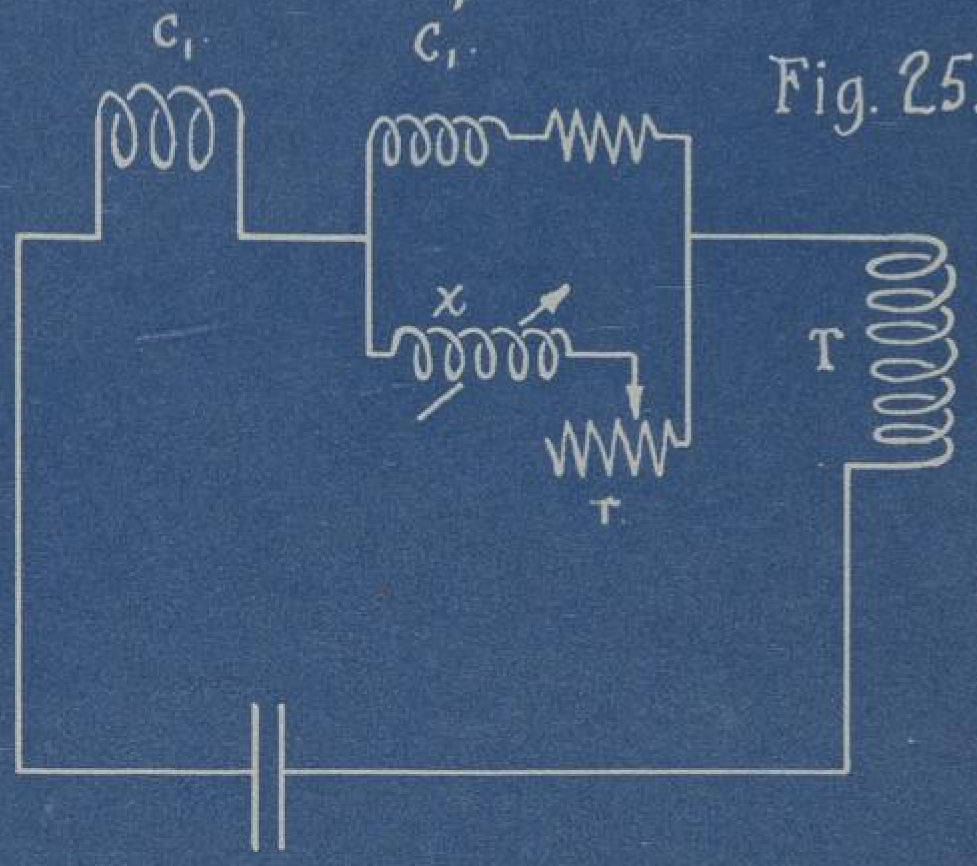


Fig. 25.



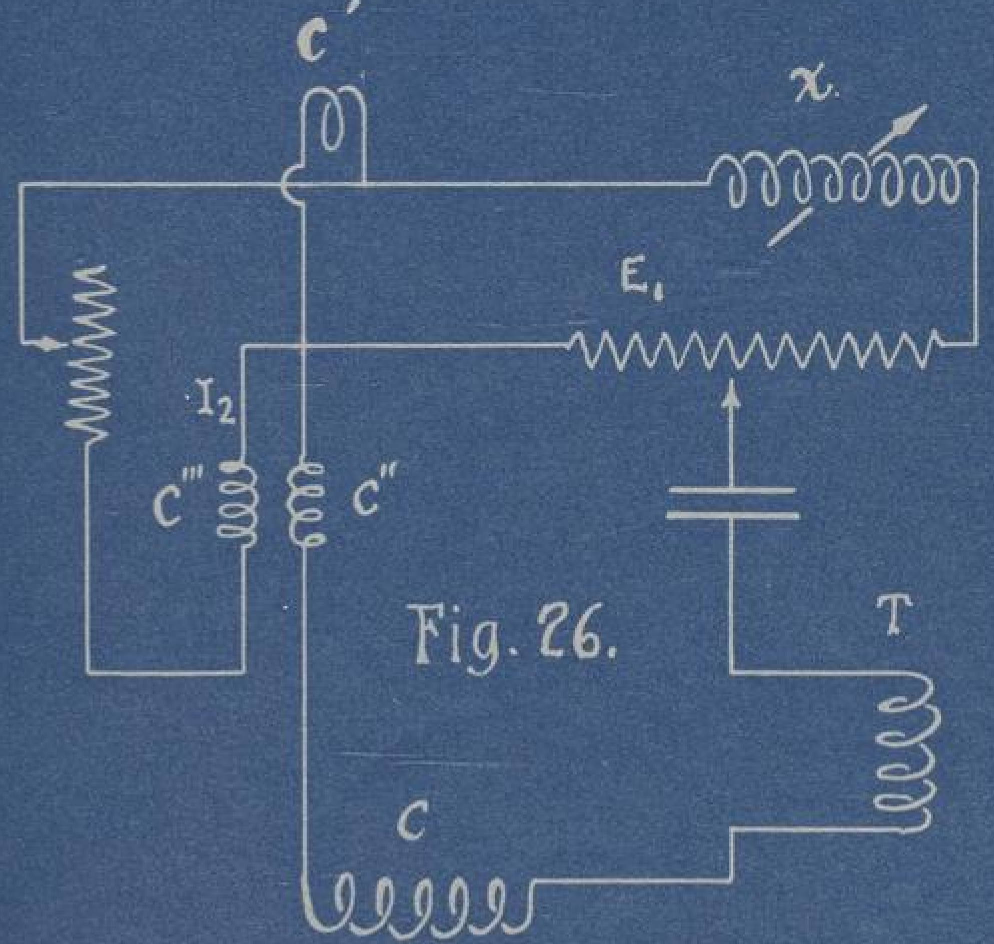


Fig. 26.

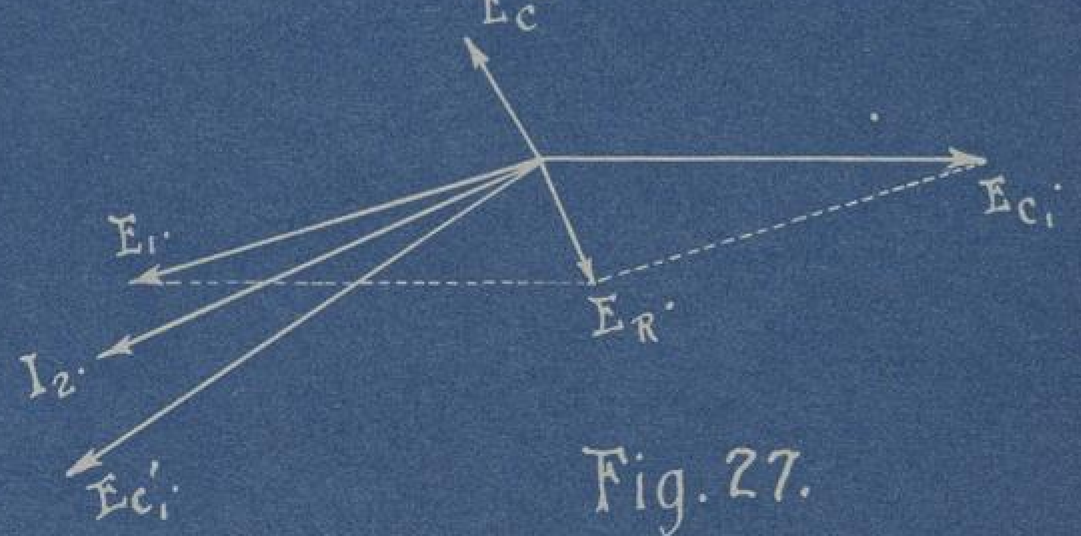


Fig. 27.

(3) Insertion of an electromotive force exactly equal and opposite to the residual electromotive force from a Drysdale alternating current potentiometer arranged as a variometer:

(a) Excited by split phase from the main generator.

(b) Excited from a small 2-phase generator mounted on the shaft of the main generator.

(4) Omit the balancing coil and insert in the detecting circuit an electromotive force from the variometer exactly equal and opposite to the electromotive force in the detecting coil due to the main magnet field.

The residual electromotive force may be neutralized by any one of the methods mentioned above, by the following experimental adjustments:

(1) Set the commutator for maximum current due to electromotive force in the detecting coil. (See Figure 23).

(2) Balance C and C' by varying position or angle of C.

(3) Shift commutator 90 electrical degrees, that is, for maximum current due to residual electromotive force.

(4) Balance out the residual by resistance drop over resistance in series with magnet winding, or by any of the other methods described in the foregoing paragraph.

(5) Shift commutator back 90 degrees.

(6) A greatly improved balance will result, but if not yet perfect, the above process is repeated.

By the above methods the conditions of the balance were greatly improved, but they were still found to be very sensitive to changes in frequency. Although the residual was found to be balanced out, there was always to be found, by rotating the commutator or by taking

an oscillogram (see Figure 24), a highly distorted wave of current in the detecting circuit. The presence of this wave can be detected simply by rotating the brushes about the commutator, taking readings at different positions. Figure 24 shows a curve taken in this way, after the system is balanced and the 30 cycle residual removed, as far as possible, by one of the methods mentioned above. Obviously the curve of Figure 24 does not show the true wave form, but serves only to indicate the presence of a disturbance made up of higher harmonic frequencies.

None of the foregoing methods of eliminating the residual electromotive force eliminated the disturbance due to frequency variation and several of them made this type of disturbance even worse.

DISTURBANCES DUE TO CHANGES OF FREQUENCY.

As has been already stated, the electromotive forces in the coils C and C' differ in phase. A number of causes for this may exist but the most obvious appears to lie in the difference in phase between the magnetic or stray field of the magnet winding alone, and that due to the main flux in the core of the magnet. These two fields differ in phase and combine in varying relative magnitudes at different points. This appears to be borne out by the fact that there is an increasing lag in phase with increasing distance from each of the magnets, M_1, M_2 and M_3. However, it will also be recalled that in close proximity to other magnetic and conducting masses there is also a shift in the phase of the magnetic field, undoubtedly due to magnetic and electric reactions of these masses. Whatever be the nature of the explanation of the shift in phase of the main magnetic field, it is obvious that the phase pertaining to any particular point will be different for different values of frequency.

The fields in the detecting and balancing coils are not unidirectional, but are rotating. This was readily determined experimen-

tally in attempting to rotate a detecting coil so that its plane should be parallel to the field, and thus have in it no electromotive force. No such position could be found, and by the means mentioned it was readily possible to measure the relative magnitude of the two components of the rotating elliptical field at any point. For example, the magnitude of the right angle component in one position of M_1 was found to vary with the position of C between 1% and 2% of the principal component. With a change of frequency the relative magnitudes of these two components will also change.

In view of the foregoing, it would appear that the following are the principal causes which may lead to an upset of the electrical balance in the detecting circuit when a slight change of frequency occurs.

(1) Inequality of phase between C and C'. Referring to the vector diagram in Figure 1, if there exists a residual electromotive force R due to a difference in phase between C and C', a change of frequency will shift the position of the parallelogram and bring a component of R into the setting of the commutator. With a residual present equal to 50 divisions on the galvanometer a change of phase of 11° would produce a deflection of 10 divisions.

(2) If C and C' are in exact opposition in phase, a change in frequency will, in general, result in a shifting of the phases of C and C' in different amounts. This will cause a resultant electromotive force between them, a greater or less component of which will appear in the setting of the commutator. A simple calculation shows that in the case of M_3 and C_3 in the relative positions used on board ship, a phase difference .025 seconds would cause a deflection of 10 divisions on the galvanometer.

(3) If C' is shunted so as to bring the electromotive force at its terminals into exact opposition with the electromotive force in C at one frequency, a change in this frequency will result in a change in both magnitude and phase of the electromotive force at the terminals of C'.

(4) Since the magnetic fields at both C and C' are rotating, a change of frequency will change the relative value of the principal and right angle components of these fields and, in general, by different amounts in the two coils, and so will result in an upsetting of the balance.

(5) Under the best conditions of balance obtained, it has always been found that there is a residual current in the detecting circuit having a complicated wave form. This harmonic residual in the balanced condition is chopped up by the commutator for normal frequency. A change in the fundamental frequency will be multiplied correspondingly for higher harmonics which would naturally result in a displacement of the harmonic residual, so that it is no longer chopped up by the commutator, thus resulting in a zero upset.

COMPENSATION OF FREQUENCY DISTURBANCE.

Since disturbances due to frequency variation may be caused by any one of the methods mentioned in the foregoing paragraph, it is obvious that it should be possible, by the introduction of one or more of these causes, to compensate the existing disturbance in a particular location and arrangement of the whole detecting equipment. For example, out of a great number of combinations which were tried, the two following may be mentioned:

(a) Balancing C against a derived circuit on C', the characteristics of this latter circuit being so adjusted that the zero upset resulting from a small frequency change was as nearly as possible a

minimum. This adjustment could be made by a cut and try method, using a definite frequency change in successive trials.

(b) With C and C' balanced as in the simple circuit of Figure 2, to balance out their resultant with a derived electromotive force, the characteristics of which were chosen so that the zero upset for a given small change of frequency was as nearly as possible zero.

An illustration of the type of circuit used for class (a) may be seen in Figure 25, where C is balanced against an electromotive force across X and R. Figure 26 shows a combination of the two, in which E_C is balanced against the resultant of E_1 and $E_{C''}$. Here it is possible to vary the effect of frequency on both the electromotive forces used to balance the electromotive force of C. E_1 is, in general, not in exact opposition of phase with E_C. The resultant of E_1 and $E_{C''}$ however may be brought into exact opposition.

These methods of eliminating a given frequency disturbance had two serious drawbacks:

(a) The amount of manipulation necessary to obtain the balance and

(b) the resultant balance, although independent of a frequency change of a given magnitude, still had a large zero disturbance in the final balanced position. The exact cause of this disturbance could not be found, but it is assumed that compensation for a frequency change of one amount is not necessarily effective for a frequency change of a different amount.

Two conspicuous conclusions resulted from the work indicated in the foregoing; the first, the more complete coincidence of phase in electromotive forces in C and C', the less the disturbance of the balanse conditions by change in speed of the generator; and second, it is always possible to overtake an improvement in speed control by such increase in sensitivity as will still leave speed variations as a limiting factor to sensitivity of the detecting circuit.

FINAL TECHNIQUE FOR OBTAINING BALANCE.

Since it is not possible to compensate all frequency variations, it appeared best to maintain the speed as nearly constant as possible and then adopt the simplest method available for bringing the electromotive forces in G and C' into exact opposition of phase. The two most satisfactory methods for speed control are described in Appendix E.

As already stated, the phase of the field due to the magnet lags more and more the greater the distance from the magnet. Unless therefore either C or C' is in close proximity to a large magnetic mass, it will be found that the phase of the electromotive force in C' leads that in C, since C', owing to its small size, is always nearer to the magnet. If now C' be shunted by a non-inductive resistance, the value of this resistance may be so chosen that the electromotive force at its terminals is exactly in phase with the electromotive force in C. The magnitude of the electromotive force at the terminals may be varied by rotating C' in the main magnetic field. Since C' and the shunt resistance may both be located within convenient reach on the observer's table, this appears as simple a method as may be found. Following are the successive steps in obtaining a balance by this means:

(1) Set commutator for the maximum signal due to the electromotive force in the detecting coil C, by setting for zero deflection, (see page 77).

(2) Shift the commutator brushes 90° and balance out the electromotive force due to C by rotating C'.

(3) Shift commutator back 90° and balance out the residual by varying the resistance in shunt with C'.

(4) Repeat (2) and (3) until the out-of-phase component is out and a good balance results.

Very often the proper value of shunt resistance may be found by noting the magnitude of the vibration, or "wiggle", of the galvanometer needle. A variation of the shunt resistance is reflected in the amplitude of this vibration. This method obviates the necessity of shifting the commutator away from the position (2), but is not as exact as the complete outline, as given.

Ordinarily only a few minutes are required to make the complete balance adjustment, and once made a single adjustment is usually sufficient to rebalance after any upset of balance due to slow temperature changes.

OTHER DISTURBANCES.

The stability of the balance may be affected by a number of extraneous causes, and some encountered in this work are mentioned below:

(1) Inductive disturbance from circuits and machines even at considerable distances from the detecting circuit. These disturbances could, in some cases, be neutralized by placing a loop of the offending circuit in proper relation to the detecting circuit.

(2) Temperature changes often caused slow creeps of the galvanometer zero. These changes are usually present unless the whole equipment has been warmed up by a sustained period of operation.

(3) The harmonic residual always present in the best balances appeared at maximum sensitivity as a vibration or shake of the galvanometer needle, quite different in appearance from the wiggle mentioned above. These disturbances may be eliminated by means of filters, or pilot conductors. (See Appendix C).

(4) Mechanical vibration of the amplifier. On shipboard this was completely obviated by spring suspension of the amplifier.

The many refinements of adjustment and elimination of disturbances, suggested in the foregoing paragraphs, were studied and used

principally in the tests on shore. On shipboard the conditions, as regards mechanical vibration due to the engines and motion in the sea, became the limiting factor when the sensitivity was increased. Although, as stated, S. C. #326 was an unusually steady boat, it was nevertheless found that the changes in the relative position of the magnet, detecting and balancing coils, was the limiting factor; consequently, it was not possible to use the extremes of amplification and sensitivity that have been used on shore. Nevertheless, the care which had been given to the elimination of disturbances had resulted in such an improvement in the general makeup of the equipment that it was possible to use between three and four stages of amplification in increasing the sensitivity. This was approximately one stage less than used in the best shore tests, and consequently many of the refinements necessary in the latter tests for eliminating disturbances were not necessary on shipboard.

OTHER FORMS OF BALANCE.

The foregoing discussion refers particularly to the arrangements A and B of Figure 1. A number of other arrangements of the detecting coil were tried, but without noticeable advantage. One of these should be mentioned, namely, that in which the detecting coil is arranged with its plane parallel to the direction of the field of the main magnet. This arrangement is not practicable, by reason of the presence of the right angle component of the rotating magnetic field. This component has to be balanced out and it appears to be extremely sensitive to frequency changes. It is possible that with further investigation and study this arrangement could be used. It has the great advantage that the electromotive force in the detecting coil is small and that therefore it can be balanced out by an electromotive force correspondingly small. Since the balance of large

electromotive forces makes it correspondingly difficult to balance out their residual, it would appear that this method has some promise.

APPENDIX H.

THE STEEL HULL AS A MAGNET.

A serious limitation of the method of detection described in the body of this report is the requirement that the detecting vessel be of wooden construction. It is obviously highly desirable that any method of detection should be suitable for installation on a destroyer or other type of patrol vessel having a steel hull. The possibility of using the steel hull as the core of the magnet was suggested by Lieutenant Colonel Mershon early in the investigations. A number of experiments were made at Johns Hopkins University on the submarine models which have been described in other parts of this report.

The models used were those which have been described as S_x and S_y and which in these experiments and the accompanying figures and curves designated D_{xx} and D_{yy}. A coil of 234 turns of #10 B. & S. magnet wire was placed around the model at its centre and excited with 80 volts, 30 cycles of alternating current. Experiments were made with D_{xx} in its original form and also after it had been slit longitudinally, i.e., along one element through its entire length.

The detecting coils used were about 1 ft. in diameter and had 300 turns each. They were flexible so that they could be fitted closely to the sides of the model. In one arrangement two of these coils were balanced against each other, one being placed on each side of the model near the bow, as indicated in Figure 28.

The distribution of the magnetic flux over the length of the model is shown in Fig. 31, where the alternates represent the electromotive force in a test coil located at different positions along the length. The distribution is seen to be closely the same for models of different thickness and also for the model which was slit from one end to the other along one element.

An interesting and important feature, in its bearing on the use of the hull as a magnet, is the variation in phase of the flux in passing along the length. The phase of the electromotive force in the exploring coil could be determined simply by the rectifying commutator and detecting instrument. The total variation in phase of the main flux passing from the magnetising coil to the end of the model was found to be 46.5° for D_{xx}. 23.4° for D_{xx} slit, and 48° for D_{yy}. This variation of phase is shown in the smaller curves of Figure 31.

The serious limitation of the use of the hull as a magnet, as indicated by the experiments, is in the difficulty of maintaining a satisfactory balance in the detecting circuit. Several methods of balancing and disposition of coils were tried as follows:

(1) With the coils in the position of Figure 28, one or both coils were shunted with resistances, taps on which afforded the voltage changes required for balancing. (See Fig. 29, in which T is the primary of the transformer feeding into the amplifier and detecting instrument). The phase changes necessary were obtained by moving one or both of the coils lengthwise over the surface of the hull. With the coils in the positions shown in Figure 28, this gave the best of all the balances studied in these tests.

(2) The detecting coil was placed near the end of the destroyer in the position indicated in Figure 30. In this case the attempt was made to set the coil parallel to the field and so obtain a minimum e.m.f. No position of zero e.m.f. was found and in fact the right angle component of the rotating field was so great that it was not possible to secure a balance in this way.

(3) An attempt was made to balance a coil placed round the bow of the destroyer against portions of one placed at the centre. It seemed possible that the submarine to be detected might cause a

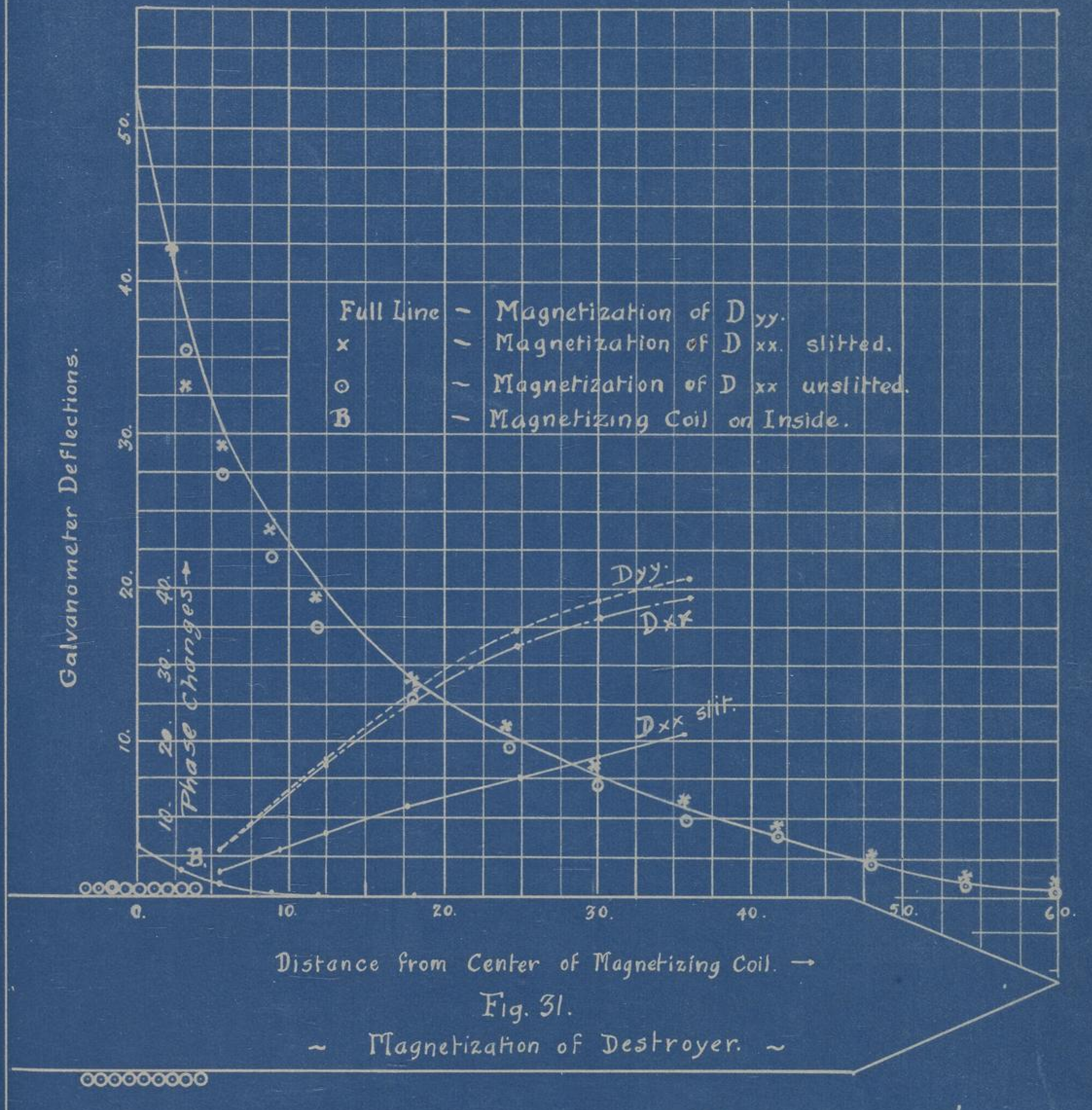


Fig. 31.

~ Magnetization of Destroyer. ~

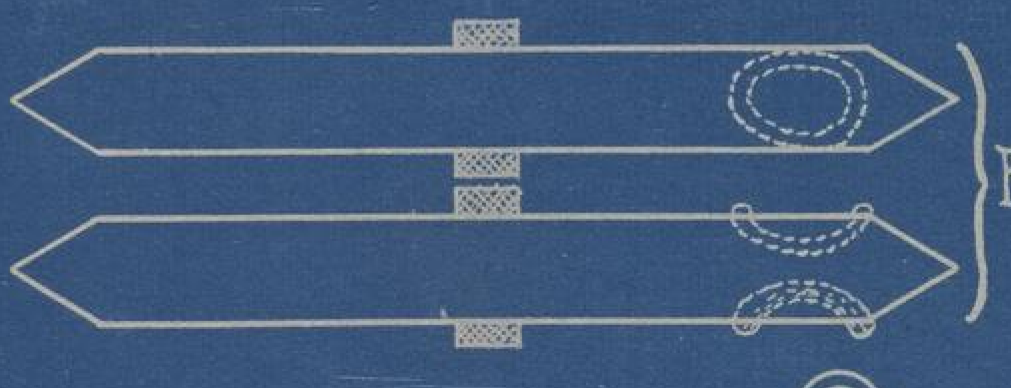


Fig. 28.

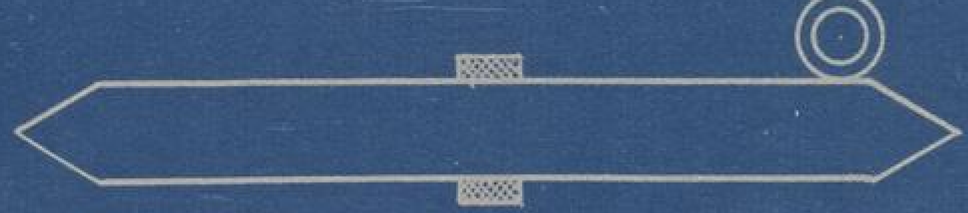


Fig. 30.

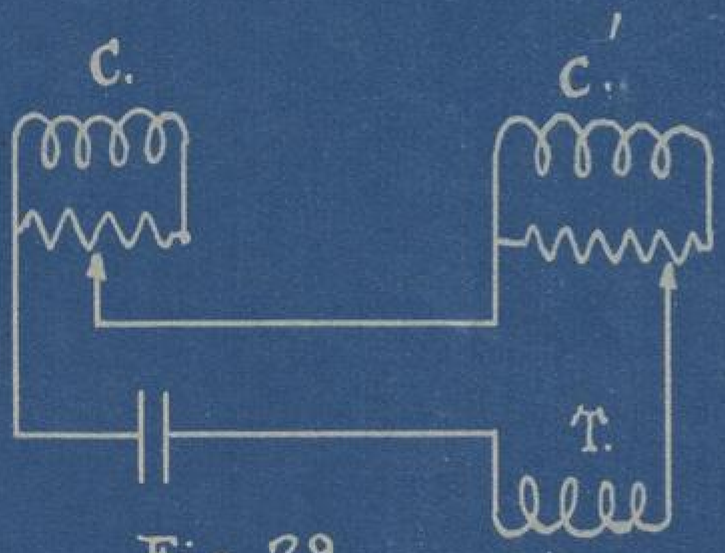


Fig. 29.

variation of some magnitude in the normal balance of two such coils. The arrangement was not practicable, however, on account of the serious phase difference between the electromotive forces in the two coils.

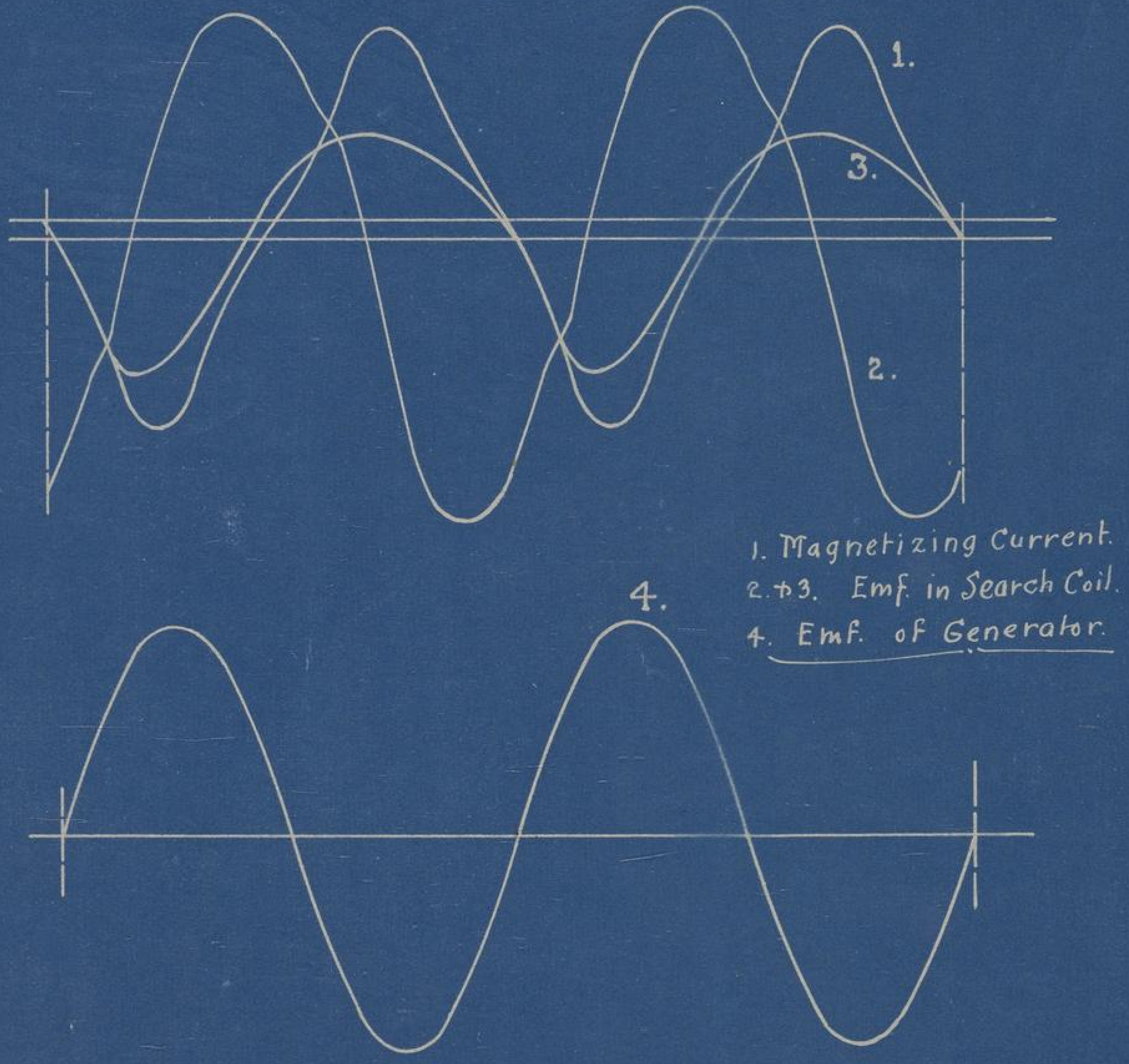
In all cases it was tedious to obtain a workable balance. The great difficulty was found to lie in the rapid variation of phase as between different positions of the coil along the side of the hull. If the position of the coil was varied to correct for phase difference, a large magnitude difference was introduced at the same time. The best balances which were obtained were very sensitive to variations of frequency and were, in general, less satisfactory than those pertaining to the experiments with a magnet having laminated core and distributed winding. The balance was found to be extremely sensitive to changes of temperature. Due to eddy currents the temperature of the hull of the model rose considerably to the centre, tapering off towards the ends. A glass of water thrown on one side of the hull caused a violent upset of the balance.

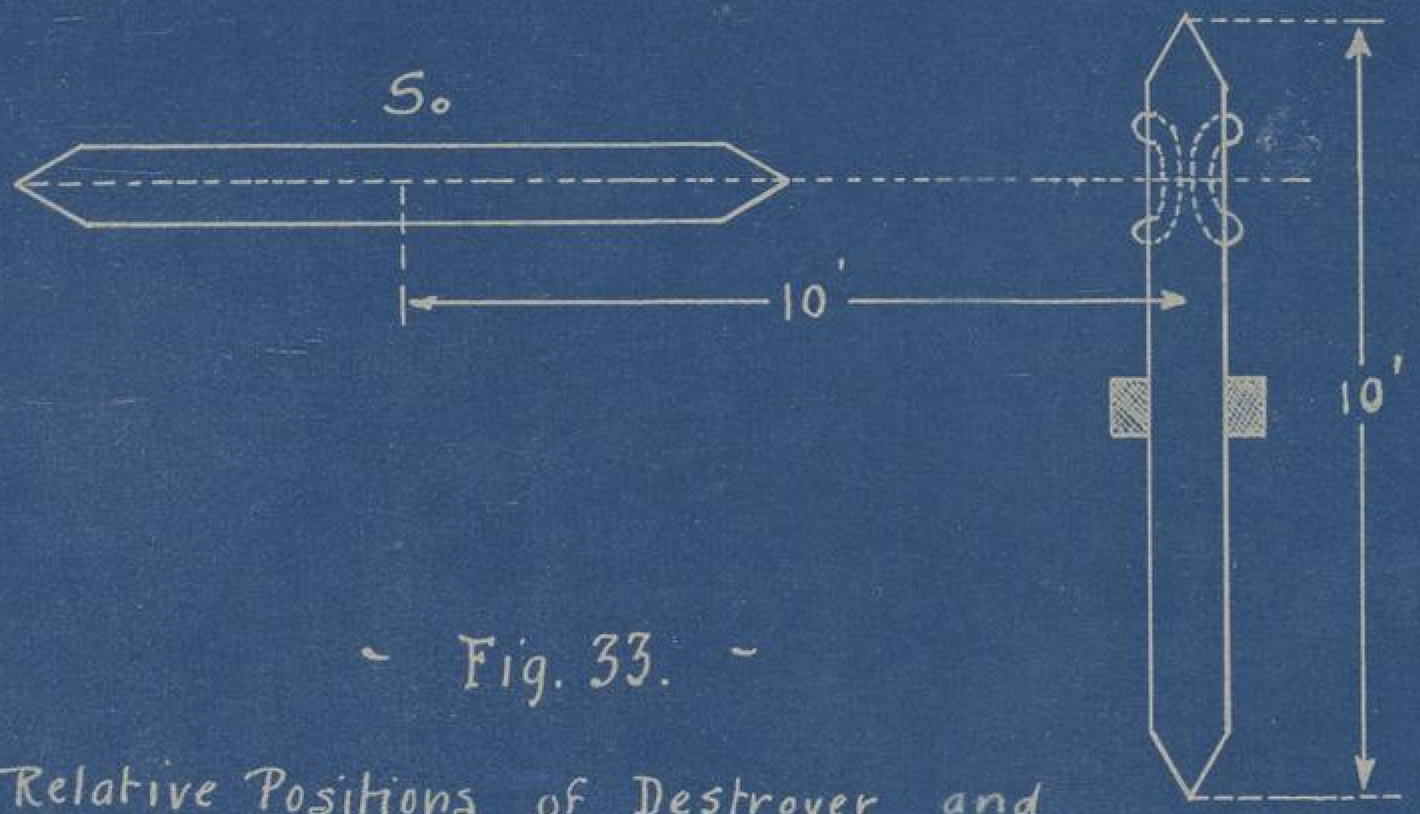
A part of the trouble with the balancing was found to lie in the presence of harmonics in the electromotive forces in the detecting circuit. Figure 32 shows in curve 1 the magnetising current, curve 2 the electromotive force in the exploring coil when placed around the hull near the magnetising coil, and curve 3 the electromotive force in the exploring coil when flattened against the side of the model near the bow. Curve 4 shows the electromotive force of the generator. These curves were all closely copied from oscillograms. In the experiments the harmonic components present were eliminated by the use of a filter. (See Figure 13).

On account of the difficulty in balancing, the maximum sensitivity in amplifier and detecting instrument could not be used. A number of rough detection observations were taken, however, of which

~ Oscillograms of Destroyer Field. ~

Fig. 32.





~ Fig. 33. ~

Relative Positions of Destroyer and ~ Submarine. ~

the most promising were in the relative positions shown in Figure 33. With S_0 in the position shown, and 10 ft. between centres and detecting coils flattened against the side, the following readings were obtained:

With D_{xx} 30 divisions

With D_{yy} 20 divisions.

Using the 2000 turn coil, C_1, as used in the experiments with the magnet, the coil being set parallel to the field on the deck of the destroyer, as shown in Figure 30, with S_0 at 10 ft., the deflections were for D_{xx} 35 divisions, and D_{yy} 50 divisions.

The experiments with the magnetised model appear not to offer any very great promise for the use of this method. It is probable that the most promising direction in which further study of the method could be made would be in a more uniform magnetisation of the hull by applying additional coils further away from the centre, and working the hull at a much lower flux density. In this way there should be less trouble with differences in phase in the balancing coil and also less possibility of disturbances due to temperature variations. It is also certain that the problem of balancing would be very greatly facilitated by the use of a variometer by which the electromotive force in the detecting coil could be balanced, thus obviating the necessity of obtaining a balance by moving a balancing coil.